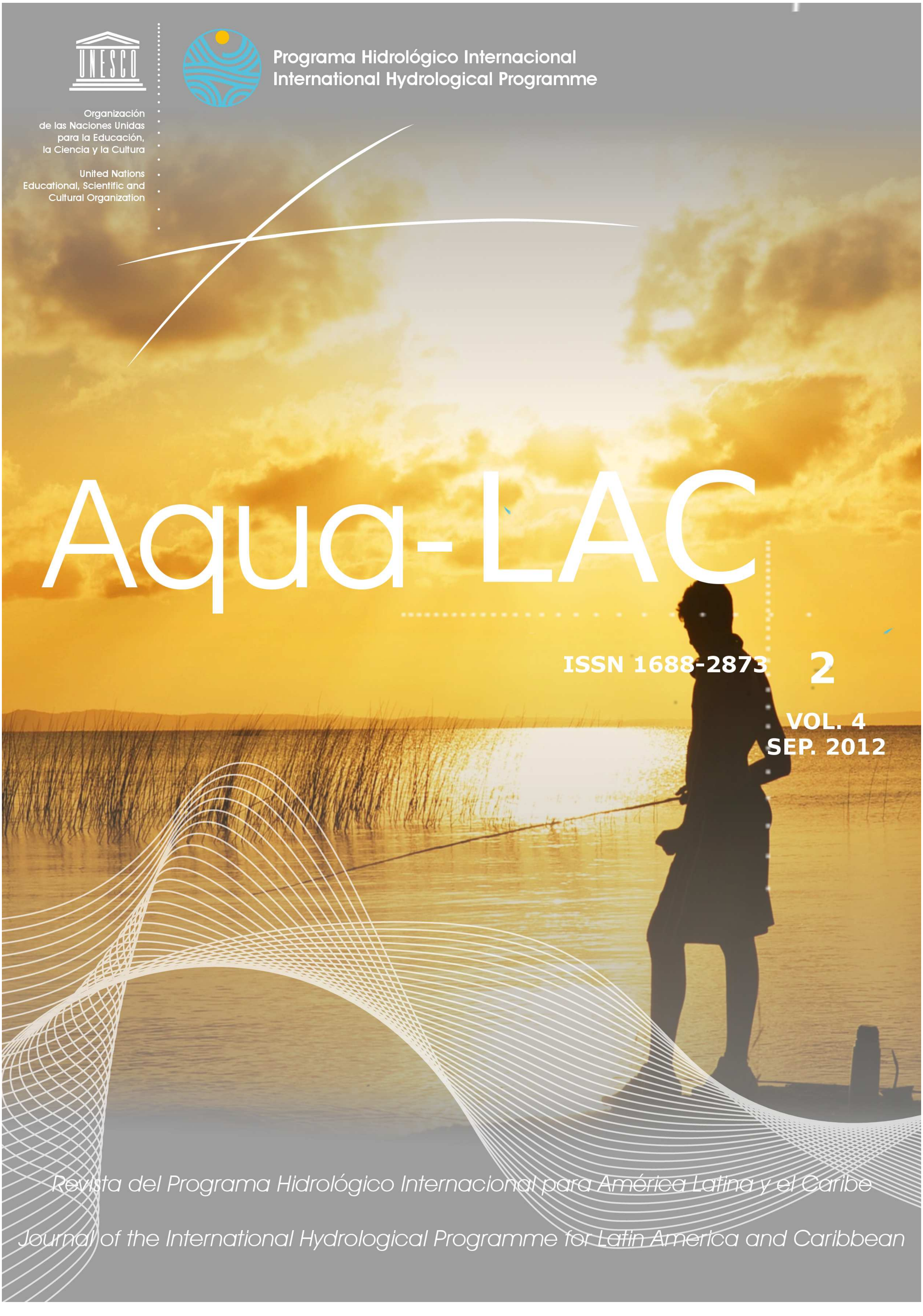

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EDITORIAL

Muy poca agua, mucha agua, sea cual sea el caso: inundaciones o sequías, el evento extremo se convierte en un desastre cuando la humanidad se ve afectada, causando daños, muertes y trastornos. El agua está mal distribuida en el mundo, desperdiciada, contaminada, y sobre utilizada. Las consecuencias son bien conocidas, las proyecciones a futuro son catastróficas. Los desastres naturales son un elemento más a incluir en los problemas relacionados con el agua.

En las últimas décadas, inundaciones, sequías y huracanes han sido los desastres naturales que han ocurrido más frecuentemente, representando casi el 90% de este tipo de eventos. Informes recientes han demostrado que los desastres relacionados con el agua están en constante aumento, se vuelven más frecuentes en la mayoría de regiones del mundo, causando enormes daños económicos y ambientales. El Instituto Universitario de las Naciones Unidas para el Medio Ambiente y la Seguridad Humana advierte que para el 2050, 2 billones de personas podrían verse afectadas como consecuencia del aumento de la población en zonas inundables, el cambio climático, la deforestación, la pérdida de los humedales y el aumento del nivel del mar.

Si bien el número de desastres relacionados con el agua ha aumentado, las muertes han disminuido considerablemente en todo el mundo gracias a la mejora de la gestión de desastres. Sin embargo, las enfermedades epidémicas transmitidas a través del agua han mostrado una tendencia creciente, por lo general como consecuencia de inundaciones, en especial en los países más pobres. La reducción de las epidemias transmitidas a través del agua y la pérdida de vidas y pertenencias requiere de una mayor comprensión de las tendencias y previsión de los desastres así como de sus riesgos y vulnerabilidades. Siendo este el caso, es necesario mejorar la vigilancia y el conocimiento en profundidad sobre el tema así como que los gobiernos adopten la gestión de desastres relacionados con el agua como una prioridad de planificación nacional, promoviendo de este modo un mayor conciencia y preparación ante las amenazas.

Basados en este entendimiento, el Centro Internacional HidroEx ha organizado una serie de talleres y cursos cortos sobre desastres relacionados con el agua. Creado bajo los auspicios de la UNESCO, HidroEx tiene la responsabilidad de ejecutar programas de desarrollo sostenible, centrándose en la conservación del agua y la gestión de los recursos hídricos mediante la educación, la investigación e iniciativas de fortalecimiento de capacidades.

En noviembre de 2010, HidroEx organizó un taller relacionado con desastres vinculados al agua en Uberaba, MG, Brasil. En esa oportunidad, se contó con la contribución de especialistas nacionales e internacionales provenientes de instituciones de investigación de Brasil, Japón, Estados Unidos, Portugal e Irán, volcados a la investigación y estudio del agua desde la ingeniería civil e hidráulica, ingeniería ambiental y saneamiento, drenaje urbano, gestión de recursos hídricos, monitoreo de inundaciones, modelación matemática hidráulica, limnología e hidrología.

Los documentos incluidos en esta edición de Aqua-LAC son el resultado de este taller y es un honor para HidroEx poder contribuir a mantener esta temática tan importante en la agenda.

Tânia A. S. Brito
Directora de Investigación – Centro Internacional HidroEX

EDITORIAL

Too little water, too much water – whatever the case may be, flood or drought, the extreme event becomes a disaster whenever humankind is affected, causing damage, death and disruption. All around the world, water is badly distributed, spoiled, contaminated, and overused. The consequences are well known, the future projections are catastrophic. The natural disasters are a further ingredient to the problems related to water.

In the last decades, floods, droughts and windstorms have been the most frequent natural disasters, accounting for almost 90% of such events. Recent reports have shown that water-related disasters are continuously increasing and becoming more frequent in most regions throughout the world, causing enormous economic and environmental damages. The United Nations University Institute for Environment and Human Security warns that as many as 2 billion people might be affected, by 2050, as a consequence of rising populations in flood-prone lands, climate change, deforestation, loss of wetlands and rising sea levels.

Despite the fact that the number of water-related disasters have increased, fatalities have diminished considerably worldwide, thanks to the improvement of disaster management. Nevertheless, water-borne epidemic diseases have shown an increasing trend, usually as a consequence of flooding, especially in poor countries. Reducing water-borne epidemics and loss of life and property requires a better understanding about disaster trends and foresightedness, disaster risks and vulnerabilities. That being the case, it is imperative that monitoring and in-depth knowledge on the issue be improved and Governments take water-related disaster management as a national planning priority, promoting better awareness and preparedness to hazards.

Based on this understanding, HidroEX International Centre has organized a series of workshops and short courses on water-related disasters. Created under the auspices of UNESCO, HidroEX has the responsibility for implementing sustainable development programs, focusing on water preservation and management of water resources through educational, research and capacity building initiatives.

In November of 2010, HidroEX organized the workshop Water-Related Disasters, in Uberaba, MG, Brazil, counting on the contribution of national and international specialists on the theme. Researchers on civil and hydraulic engineering, sanitation and environmental engineering, urban drainage, water resources and management, flood control, hydraulic mathematical modeling, limnology and hydrology, from research institutions in Brazil, Japan, United States, Portugal and Iran took part in the event.

The papers present in this issue of Aqua-LAC are a result of this workshop and HidroEX is honored to be able to contribute to keep on the agenda such an important issue.

Tânia A. S. Brito
Director of Research – HidroEX International Centre

POLÍTICA EDITORIAL

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La revista Aqua-LAC es una publicación multidisciplinaria que contiene artículos, notas técnicas y reseñas en el campo de los recursos hídricos, tanto en su dimensión científica como en su dimensión económica y social. El contenido de la publicación buscará abarcar las necesidades de la comunidad científica, gestores de los recursos hídricos, tomadores de decisiones y el público en general.

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The journal Aqua-LAC contains scientific, policy-related, legislative, educational, social, and communication articles and revisions related to water sciences and water resources topics. The content of the journal is aimed to meet the requirement of the scientific community, water resources managers, decision-makers, and the public in general.

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All manuscripts submitted for publication will be reviewed by at least two qualified reviewers, not necessarily members of the Editorial Committee. A manuscript can be accepted with or without comments or it can be rejected with due justification. In the first case, the manuscript will be returned to the author(s) for him/her/them to address the comments. The author(s) will have 60 days to return the modified manuscript to the Editor in Chief, clearly indicating the changes made or providing a written statement with solid fundaments for not addressing comments by the reviewers.

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INUNDAÇÕES URBANAS EM BELO HORIZONTE. OCORRÊNCIAS, CONTROLE E MEDIDAS DE PROTEÇÃO

URBAN FLOODING IN BELO HORIZONTE OCCURRENCES, CONTROL AND PROTECTIVE MEASURES

INUNDACIONES URBANAS EN BELO HORIZONTE OCURRENCIAS, CONTROL Y MEDIDAS DE PROTECCIÓN

José Roberto B. Champs

RESUMO:

Apresenta-se a metodologia adotada para identificação da série histórica de inundações na cidade de Belo Horizonte, realizada com base em levantamento de informações de arquivo da imprensa local no período de 72 anos, uma vez que a cidade somente implantou uma rede de monitoramento hidrológico no ano de 2012. Os dados obtidos indicaram estreita correlação entre os eventos de inundação, o crescimento populacional, a expansão urbana da cidade e a distribuição anual das precipitações ocorrentes no território do município de Belo Horizonte.

Este trabalho apresenta também os fatores que determinaram a crise do sistema convencional de drenagem, as medidas de planejamento e as ações de regularização de cheias adotadas pela Administração Pública Municipal com o objetivo de superar esta crise e reduzir as ocorrências das inundações.

Palavras-chave: Inundações, drenagem pluvial, planejamento urbano, monitoramento hidrológico, regularização de cheias.

ABSTRACT:

This report presents the methodology used to identify the historical series of floods in the city of Belo Horizonte, carried out based on survey information of the local press file, in the period of 72 years, since the city only established a hydrological monitoring network in the year of 2012. The data indicated a high correlation between flood events, population growth, urban expansion of the city and annual distribution of rainfall occurring in Belo Horizonte. This paper also presents the factors that determined the crisis of the conventional drainage system, the planning measures and the actions for the regularization of floods taken by the Municipal Public Administration in order to overcome this crisis and reduce the occurrences of floods.

Keywords: Flooding, storm drainage, urban planning, hydrological monitoring, flood regulating.

RESUMEN:

Se presenta una metodología para la identificación de la serie de inundaciones en la ciudad de Belo Horizonte, realizada a partir de informaciónes del archivo de la prensa local en el período de 72 años, porque la ciudad sólo se implementó una red de monitoreo hidrológico en el año 2012. Los datos indican una estrecha correlación entre las inundaciones, el crecimiento demográfico, la expansión urbana de la ciudad y la distribución anual de las lluvias que se producen en el municipio de Belo Horizonte. Este documento también presenta los factores que determinaron la crisis del sistema de drenaje convencional, las medidas de planificación y las acciones de regularización de las inundaciones tomadas por la Administración Pública Municipal con el fin de superar esta crisis y reducir la ocurrencia de inundaciones.

Palabras clave: Inundaciones, drenaje, planificación urbana, la vigilancia hidrológica, regularización de las inundaciones.

INTRODUÇÃO

Belo Horizonte é a capital do Estado de Minas Gerais, Brasil, com população de 2.350.000 habitantes e território de 330 km^2.

A cidade sofre, desde sua fundação em 1897, com contínuas e sempre crescentes inundações anuais. Em razão de tal situação a Administração Municipal elaborou entre os anos de 1.999 e 2.001 um Plano Diretor de Drenagem Urbana.

A fase inicial deste Plano foi dedicada à elaboração dos diagnósticos da realidade física do sistema de macrodrenagem e da hidrografia local, do histórico de ocorrência de cheias e de inundações, da gestão dos serviços de drenagem pluvial, do controle e do combate às inundações.

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A primeira dificuldade encontrada se deveu à inexistência de um serviço de hidrometria pluvial e fluvial, resultando em uma escassez de dados sobre a distribuição e frequência dos eventos de chuva. A solução encontrada foi a de se recorrer aos registros da mídia impressa local, a qual contém em seus arquivos notícias de eventos de inundações ocorridos desde o ano de 1.932. Assim sendo, foi feito um levantamento de tais notícias ao longo de 72 anos de existência da cidade, possibilitando desse modo identificar com razoável confiabilidade a distribuição e frequência das inundações ocorrentes no território da cidade.

Com a conclusão do Plano Diretor de Drenagem em 2.002, foi possível elaborar planos subsequentes para todo o contexto das águas urbanas nas bacias hidrográficas que contém o território do Município, configurando novos modelos de organização, operação e gestão dos serviços de drenagem.

IDENTIFICAÇÃO DO HISTÓRICO DE INUNDAÇÕES – METODOLOGIA DE TRABALHO

Tendo em vista o fato de não existir um banco de dados sobre inundações urbanas em Belo Horizonte, recorreu-se à única fonte de informações disponível que são os arquivos da imprensa escrita local. Se por um lado tais dados apresentam uma imprecisão técnica, têm, no entanto, várias utilidades e vantagens tais como o registro cronológico e localização das ocorrências, informações sobre danos físicos, acidentes e fatalidades, revelando elementos suficientes para identificação dos eventos históricos.

O veículo de imprensa escolhido para a pesquisa foi o jornal “O Estado de Minas”, pela sua longevidade, pela continuidade das publicações e, sobretudo, pela existência de um acervo de edições arquivadas. Este jornal foi fundado em março de 1928, mas a primeira notícia de interesse para a pesquisa foi dada somente em 11 de janeiro de 1932 registrando uma inundação provocada pelo transbordamento das águas do principal ribeirão existente na cidade (Ribeirão Arrudas) que atingiu áreas situadas desde a região noroeste da cidade até a região leste – incluindo a área central – causando a destruição de duas pontes e de várias habitações ribeirinhas. A ultima data verificada foi 18 de fevereiro de 2.000, completando-se, assim, os 72 anos desta investigação.

Critérios para seleção das notícias

Os critérios para a seleção das notícias foram os seguintes:

a. Notícias referentes apenas à execução de obras e serviços de drenagem foram excluídas;

b. Notícias diversas para diferentes locais, porém ocorridas no mesmo dia, foram agrupadas como um único evento;

c. Sobreposições de datas iguais entre campanhas diferentes de pesquisas foram identificadas e contabilizadas como único evento.

O total de notícias registradas foi de 461 que, no entanto, ao serem submetidas aos critérios anteriormente citados resultaram em cerca de 200 eventos de significativa importância, conforme os objetivos desta pesquisa. As inundações selecionadas podem ser caracterizadas como inundações históricas uma vez que mereceram destaque na imprensa pelos danos provocados com prejuízos econômicos e, em alguns casos, com perdas de vidas humanas e invariavelmente associadas a notícias de precipitações intensas.

Resultados Obtidos

A Tabela 01 apresenta a distribuição mensal da séria histórica de inundações (1.928 a 2000), onde se pode observar que:

- Os meses de maior incidência de inundações são os meses de Dezembro e Janeiro, responsáveis por 50% das ocorrências (cada qual por 25 % destas);
- Os eventos registrados para os meses de estiagem (Abril a Setembro) correspondem a apenas 4% do total de registros de inundações.

Tabela 01 – Distribuição Mensal das Inundações Históricas - (Período de 1.928 a 2.000)

Mês	No de Inundações
Janeiro	50
Fevereiro	26
Março	17
Abril	3
Maio	1
Junho	0
Julho	1
Agosto	0
Setembro	3
Outubro	17
Novembro	31
Dezembro	51
TOTAL	200

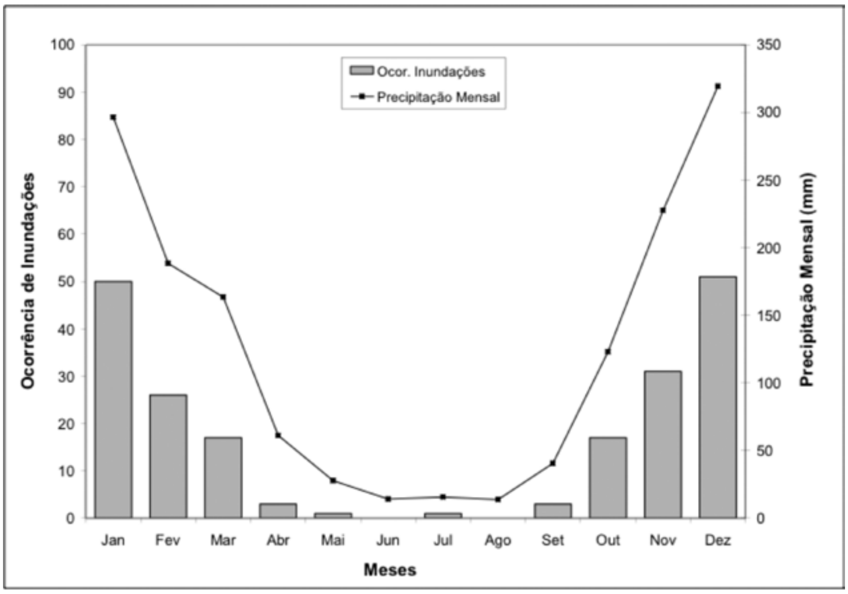

Figura 01: Série Histórica de Inundações e Precipitações Médias Mensais no município de Belo Horizonte / MG

Os resultados obtidos evidenciaram uma relação de “causa e efeito” entre as chuvas intensas (em geral, precipitações convectivas) e as inundações em Belo Horizonte. A Figura 01 ilustra as ocorrências de inundações e a distribuição mensal de precipitações.

Os registros pluviométricos são referentes à série histórica de 1.960 a 1990 da estação climatológica do 5° Distrito do Instituto Nacional de Meteorologia (INMET), localizada no município de Belo Horizonte.

Para analisar a ocorrência dos eventos de inundações ao longo do tempo, visando uma relação com o desenvolvimento da urbanização do município, foram correlacionados os registros de inundações pesquisados com os dados populacionais das décadas de 1.930 a 1.990, sendo os resultados apresentados na Figura 02.

A partir da análise dos registros de inundações pode-se concluir que:

- A década de maior incidência de inundações foi a década de 80;
- Os anos de maior ocorrência de inundações foram 1.989 e 1.998, sendo registrados 13 eventos em cada um;
- 69,5 % dos eventos de inundações aconteceram nas duas últimas décadas do século XX;
- A evolução das ocorrências de inundações acompanha a curva da evolução populacional, conforme ilustra a Figura 02.

Analisando a Figura 02, podem ser observados dois momentos distintos na série histórica de inundações. Na passagem da década de 30 para a década de 40 tem-se um primeiro pico de ocorrências de enchentes; entre 1.960/1.980, um segundo pico bem mais elevado que o anterior. Entre esses dois picos, a década de 50 é marcada por nenhuma ocorrência de inundação.

Segundo RAMOS (1.998), o primeiro pico de ocorrência de inundações pode estar relacionado com o primeiro avanço imobiliário na cidade no final da década de 20, conjugado com a intensa ocupação da zona urbana no final da década de 30. O segundo pico, por sua vez, pode ser reflexo do “boom” do processo de urbanização e parcelamento do solo e do crescimento populacional do final da década de 60.

Na imprensa, as notícias de inundações passaram a ser mais frequentes ao final dos anos 60. Nesse período, e ao longo dos anos 70, diversos eventos de inundações foram observados nos afluentes do ribeirão Arrudas e em córregos da bacia do ribeirão da Onça.

Ao longo das décadas de 80 e 90, com a ampliação do sistema de drenagem na área central e com a expansão da cidade em direção às regiões periféricas, outros pontos críticos no sistema de drenagem se evidenciaram. Na zona sul da cidade, problemas com os afluentes do Ribeirão Arrudas começaram a ocorrer nos anos 90, os quais atingiram áreas intensamente ocupadas e valorizadas. Vários desses eventos atingiram situações de calamidade, como foi a ocorrência em Janeiro de 1.983 que deixou um rastro de destruição sendo que o número de vítimas fatais chegou a 70 mortes.

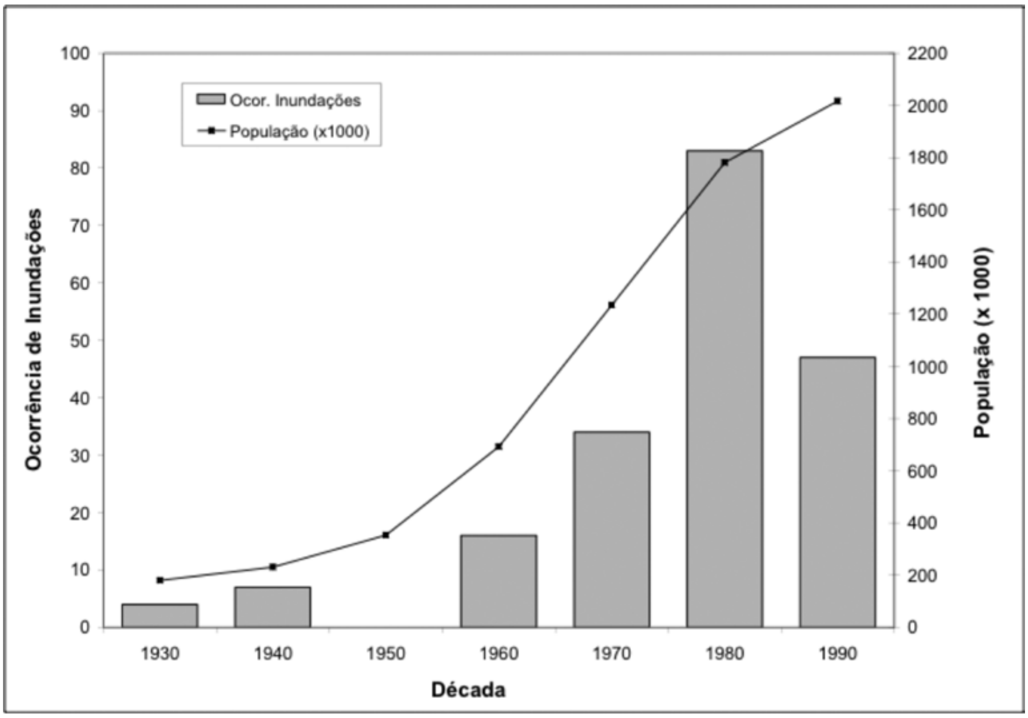

Figura 02: Evolução populacional x Ocorrências de inundações no município de Belo Horizonte / MG

A CRISE DO SISTEMA CONVENCIONAL DE DRENAGEM

A crise do sistema de drenagem na cidade de Belo Horizonte pode ser identificada através dos seguintes aspectos:

a. ambiental

O modelo de evacuação rápida das águas pluviais, obtido pelo aumento das velocidades do escoamento através de canalizações, trouxe como resultado a exclusão de parte da hidrografia natural do cenário urbano.

Em Belo Horizonte, 20% de todos os cursos d'água encontram-se confinados em estruturas de concreto, a maioria das quais enterrada sob o pavimento de avenidas "sanitárias".

As ações de saneamento implantadas nos fundos de vale não foram suficientes para sanear os cursos d'água, mesmo tendo sido construídos interceptores ao longo destas avenidas, uma vez que as águas continuaram a receber cargas poluidoras produzidas em suas bacias de drenagem.

b. financeiro

A implantação dos sistemas convencionais de drenagem, especialmente das obras de macrodrenagem, exigem grandes inversões de recursos financeiros por parte da municipalidade, limitando a abrangência dos programas de controle de cheias nas cidades. Justifica-se, assim, a busca de soluções alternativas de menor custo para implantação e também para sua manutenção.

c. operacional

As soluções baseadas no aumento das velocidades dos escoamentos trouxeram como consequência a redução dos tempos de pico das cheias e a elevação das vazões máximas, resultando em uma transferência de inundações para regiões situadas a jusante das canalizações.

UM NOVO PLANEJAMENTO PARA A DRENAGEM URBANA

Para enfrentar as deficiências do sistema convencional de drenagem e a consequente ocorrência de inundações, a Municipalidade de Belo Horizonte elaborou, no período de 1.999 a 2.002, um Plano Diretor de Drenagem Urbana, para servir de instrumento de planejamento para a gestão e operação dos serviços de controle de cheias com forte enfoque ambiental.

O Plano Diretor de Drenagem Urbana de Belo Horizonte

O Plano abrange a totalidade das bacias hidrográficas (430 km^2) de todos os cursos d'água existentes no território do Município (330 km^2).

As premissas adotadas pelo Plano foram:

a. Interdependência da drenagem com os demais sistemas urbanos;
b. Não ampliação da cheia natural, restringindo-se a ampliação da impermeabilização do solo ou criando mecanismos de compensação às novas áreas impermeabilizadas;
c. Não transferência de cheias ou de impactos de inundação resultantes do aumento da aceleração dos escoamentos;
d. Conhecimento do funcionamento real do sistema de drenagem através do monitoramento da relação chuva X vazão;
e. Compatibilização do planejamento da expansão urbana com as diretrizes de drenagem;
f. Valorização ambiental das águas enquanto paisagem urbana;
g. Estabelecimento de um processo de gestão para os serviços de drenagem;
h. Participação da comunidade na elaboração de planos e projetos relacionados aos recursos hídricos naturais existentes na cidade;
i. Desenvolvimento tecnológico e pesquisa de soluções alternativas ao sistema convencional de drenagem urbana;

Além destes princípios definidores das políticas públicas relacionadas à drenagem urbana, o Plano realizou uma completa caracterização das bacias elementares e um completo cadastro de toda a rede de micro e macrodrenagem.

UM NOVO PROGRAMA DE AÇÕES EM DRENAGEM URBANA

Com base nas propostas do Plano Diretor de Drenagem, a Municipalidade iniciou em 2.002 a implantação de um programa de ações estruturais com enfoque ambiental e sanitário abrangente para toda a cidade, priorizando as bacias hidrográficas cujos cursos d'água se encontram em seus leitos naturais. Este Programa recebeu a denominação de Programa de Recuperação Ambiental e Saneamento de Belo Horizonte (DRENURBS). As obras resultantes começaram a ser implantadas em 2.004 e encontram-se em desenvolvimento até os dias de hoje.

A proposta do Programa DRENURBS é a de se reverter a degradação em que se encontra a totalidade dos córregos não canalizados da cidade (incluindo-se o controle das cheias), combater as causas geradoras da poluição das águas que têm origem nestes fundos de vale e principalmente nas respectivas bacias de drenagem.

Configura-se, portanto, como uma perspectiva de melhoria da qualidade de vida para toda a população da cidade através de ações de melhoramento das condições ambientais.

Em consonância, com as premissas do Plano Diretor de Drenagem, o Programa DRENURBS desenvolve-se de acordo com as seguintes diretrizes:

a. Tratamento integrado dos problemas sanitários e ambientais no nível da bacia hidrográfica, utilizada como unidade para o planejamento das intervenções;
b. Limitação à ampliação da impermeabilização do solo através de proposições de tipo naturalísticas (calhas vegetadas, criação de parques lineares, corredores ecológicos etc);
c. Opção pela estocagem de águas (reservatórios de retenção / detenção) no lugar da evacuação rápida;
d. Implantação do monitoramento hidrológico para conhecimento da relação *chuva X vazão* (coincidente com a proposta para a 2ª Etapa do PDDU), enquanto item do componente "Fortalecimento Institucional";
e. Tratamento das coleções d'água enquanto paisagem urbana;
f. Adoção de técnicas alternativas aos procedimentos convencionais para as questões de drenagem; e
g. Inclusão das comunidades afetadas e usuárias dos serviços e equipamentos propostos nos projetos no processo de tomada de decisões.

O aspecto que se destaca para futuro desenvolvimento do Programa é um novo arranjo institucional para uma gestão sustentável e única para gerenciamento e operação dos sistemas de drenagem pluvial e esgotamento sanitário integrados aos demais componentes do saneamento ambiental como a coleta e o tratamento de resíduos sólidos.

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DROUGHT AS A WATER RELATED DISASTER; A CASE STUDY OF OROOMIEH LAKE

LA SEQUÍA COMO DESASTRE DE ORIGEN HÍDRICO; UN ESTUDIO DE CASO DE OROOMIEH LAKE

Homayoun Motiee(Ph.D.)[1], Alireza Salamat (M.Sc.)[2], Edward E. Mc Bean[3]

ABSTRACT

Drought is a normal phenomenon in various types of climates, but it is more prominent in arid regions like that of the Middle East of Asia where its recurrence is likely to increase in the future, in terms of both frequency and intensity. Despite the long time existence of drought, its management is still not optimal because of the way it is generally perceived and misunderstood by policy makers and experts. During recent years however, a lot of progress has been made, with a major shift from the perception of considering drought as an emergency phenomenon, to long term planning for efficient management, but efforts are still required to elaborate and implement drought mitigation plans, for which most countries are still in the need for great help to reduce their vulnerability and to build their capacity to combat drought effects.

Water management in arid and semi-arid regions is facing a crisis. Lack of water in regions with chronic shortages of water may lead to mass migration of people causing social and political problems. Drought is a weather-related natural disaster, a dangerous hazard of nature, related to a deficiency of precipitation over an extended period of time, usually for a season or more. It has an impact on food production and it reduces life expectancy and the economic performance of large regions or entire countries.

Iran is located in an arid and semi-arid geographical region and receives an average rain fall of only 250 mm per year equivalent to one third of the world's average. Therefore, many parts of Iran suffer from extreme water shortage conditions. Moreover, with a high rate of population growth, a slow pace of building reservoirs, traditional water management systems, and recent years of drought in some central and eastern parts of the country (receiving only 100 mm-precipitation / year on average) the results have contributed to a major water crisis in these areas and has made the government face one of its most difficult challenges in the past few years.

Drought as a natural disaster occurring frequently from thousands of years ago has caused severe economic, political and social damages. Major tribal migrations are due to this devastating phenomenon. Some wars happened by tribes which faced droughts with the aim of accessing water resources and fertile land located at regions with better climate which contributed in changing the history.

In this paper in addition to defining drought, information related to Iran's climate and geographical conditions has been submitted and drought impacts during the recent decade has been highlighted. The negative impacts of drought on the current situation of Lake Oroomieh as a case study in the north west of Iran have also been presented.

Key words: Drought, Lake Oroomieh, Disaster, Climate change, Iran

RESUMEN

La sequía es un fenómeno normal que ocurre en varios tipos de clima, siendo más significativa en las regiones áridas, tales como las del Medio Oriente asiático donde es probable que exista una tendencia a una mayor recurrencia en el futuro, con mayor frecuencia e intensidad. Si bien la sequía es un fenómeno que existente desde hace ya mucho tiempo, su manejo resta todavía de ser el óptimo, debido, en gran parte, a la forma en que generalmente se percibe la misma y a la mala interpretación de los expertos y responsables políticos. No obstante, durante los últimos años, ha habido un gran progreso, apreciándose un cambio significativo en la errónea percepción de considerar a la sequía como un fenómeno de alarma, para incorporar el concepto de planificar a largo plazo para una gestión eficiente. De todas formas, se requieren aún mayores esfuerzos para elaborar e implementar planes de mitigación de sequías, para lo cual la mayoría de los países necesitan aún un gran apoyo a fin de reducir su vulnerabilidad así como para aumentar su capacidad para combatir sus efectos adversos.

La gestión del agua en las regiones áridas y semiáridas está enfrentando una crisis. La falta de agua en las regiones con escasez crónica puede conducir a la migración masiva de personas causando problemas sociales y políticos. La sequía es un desastre natural vinculado al clima, un riesgo peligroso de la naturaleza que se relaciona a una deficiencia de precipitación durante un período prolongado de tiempo, por lo general durante una temporada o más. Tiene un impacto en la producción de alimentos, reduce la esperanza de vida y el desempeño económico de grandes regiones o incluso de países enteros.

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Irán se encuentra en una región geográfica árida y semiárida con una precipitación media de sólo 250 mm por año, lo que equivale a un tercio de la media mundial. Por lo tanto, muchas regiones de Irán sufren condiciones de extrema escasez de agua. Además, el alto crecimiento poblacional, el lento ritmo para la construcción de embalses, sistemas tradicionales de gestión del agua y los recientes años de sequía en algunas partes del centro y este del país (sólo reciben 100 mm de precipitación media por año) han resultado en una grave crisis de agua en estas áreas, poniendo al gobierno frente a uno de sus desafíos más difíciles de los últimos tiempos.

La sequía como desastre natural, que tiende a ocurrir frecuentemente desde hace ya miles de años, ha causado graves daños económicos, políticos y sociales. Las migraciones tribales más importantes se deben a este fenómeno devastador. Algunas de las guerras que ocurrieron antaño pueden explicarse por el enfrentamiento de tribus que, ante una sequía, buscaban acceder a los recursos de agua y tierras fértiles situados en regiones con mejor clima, lo cual contribuyó al cambio de la historia.

En este trabajo, además de encontrar una definición de sequía, se ha presentado información relacionada con el clima y las condiciones geográficas de Irán y las consecuencias que la sequía ha generado en los últimos años. También, a través de un estudio de caso, se presentan los impactos negativos que la sequía tiene sobre la situación actual del lago Oroomieh, situado en el noroeste de Irán.

Palabras clave: sequía, Lago Oroomieh, desastres, cambio climático, Irán

INTRODUCTION

Around two billion people live in countries with limited water resources called arid and semi-arid regions. Water, with its qualitative and quantitative effects, plays a critical role in economic and social expansion of societies and, unlike many other inputs, is irreplaceable. Reasons for the impending crisis include: accelerating rates of population increase, periodic droughts, climate change, and mismanagement of water resources, all of which are increasing the desertification trends. As populations grow, water use is increasing with dramatic implications to many parts of the world.

Issues of water availability have greater impacts within the arid and semi-arid regions. Not only is there over-withdrawal of groundwater, shortages of water are intensifying due to reasons including the types of agriculture taking place (e.g. the growing of rice in water-short areas), and lands which are deteriorating to desert conditions. The result is that people from these regions particularly in villages are obliged to immigrate to other regions with adequate water resources. Due to the increasingly unsustainable situation in these regions, without responses from individual governments, gradually massive migration of people will likely occur.

WMO (1975) defined drought as: “A deficit of rainfall with respect to the long term mean, affecting a large area for one or several seasons or years that drastically reduces primary production in natural ecosystems and rain-fed agriculture.” (Le Houerou, 1995)

The increase in drought intensity and duration has caused water resources and agricultural products scarcity. During the recent decades, drought frequency from the view point of intensity, duration, area under coverage, livelihood damages, and long term socio- economic damages has been higher than other natural disasters. In fact water scarcity and drought causes water pollution, environmental damages and negative impacts on fresh potable water resources supply. Figure 1 demonstrates the global drought map and as observed severe droughts have mainly occurred in the Middle East Asia.

From the other hand due to population increase, social evolution and changes in the people’s level of life, increases water requirement. In addition, precise anticipation of accessible water and appropriate planning for the existing water during drought is very important.

One of the definitions of drought is: a continuous duration of insufficient rainfall which causes severe economic damages to a country.

In order to determine the drought starting point, the deviation from the average rainfall with other climatic variations during a time period is determined and this is carried out by comparing the current situation with the past averages mainly based on thirty years of statistical data.

Drought is classified as (www.agriinfo.in):

1. Climatic drought
2. Hydrological drought
3. Agricultural drought
4. Socio-economical drought

Climatic drought definition should be made region-wise as climatic condition which causes rainfall decrease, varies from region to region.

Drought monitoring and compiling special models for anticipating and designing a risk management model is one of the most important issues which can help researchers and experts determine droughts.

When drought hits a country, all or most sectors of its economy are affected, but farmers, herders and the rural population often suffer more than the rest. Generally speaking, the more the economy of a country relies on agriculture, the more its economy is vulnerable to drought. Drought preparedness and mitigation is therefore the concern of all sectors. As shown in the following table Asia in amongst the continents which mainly suffers from droughts. North America and Africa are also drought prone areas.

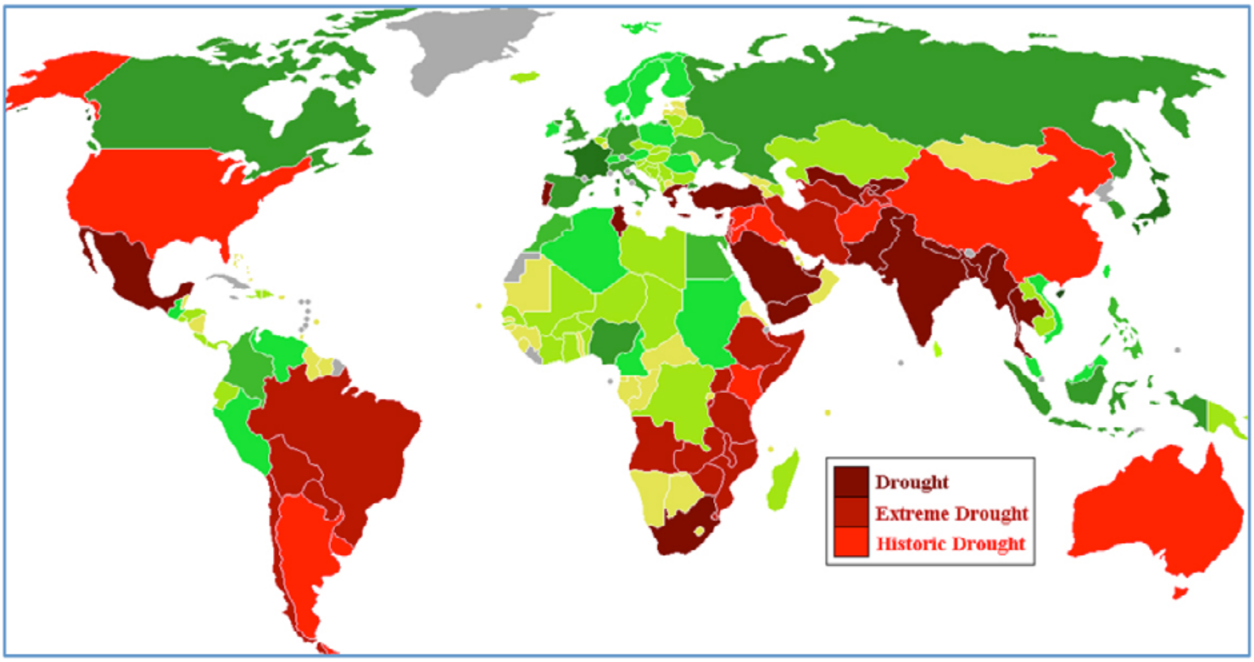

Figure 1- Global Drought Map (unitedcats.wordpress.com)

	No. of Droughts	No. of droughts ≤ 6 months	No. of droughts ≥12 months	Longest duration (months)	Maximum spatial extent (km²)
Africa	44	28	4	19(1982-84)	40.0%
Asia	86	37	22	49(1984-88)	18.5%
Europe	40	24	4	20(1959-61)	42.8%
North America	57	34	8	44(1950-53)	39.3%
Oceania	24	17	1	12(1951-52)	80.2%
South America	45	37	4	16(1958-59)	51.2%

Table 1- Summary of large-scale drought occurrences for the six continents (World Climate Report, 2010)

GEOGRAPHIC AND CLIMATE CONDITIONS OF IRAN

Iran, with a dry to semi-dry geographic environment and with an average rain fall of 250 mm/year, is facing extreme shortages of water in its southern and central parts. Sixty-five percent of Iran's area is arid, 20% is semi-arid, and only 15% of landscape is considered as wet and semi-wet. Approximately 50% of Iran's population is living in the northern and western parts of country which have over 70% fall the water resources (Motiee et al., 2001).The rapid growth of Iran's population, the slow process of building water reservoirs, and recent dry years, have caused serious water shortages in central and eastern parts of Iran (Figure 2).The country's population has increased about 7 times during the last 80 years and it has risen from 10 million in 1920 to more than 70 million in 2008. At present Iran is the 17th most populated countries in the world and based on the data presented by the UN it will be classified as one of the 10 most populated regions in the world by the end of 2050. Therefore the need for water has been increased but still the quantity of water is not adequate.

The four primary reasons for the serious water crisis in Iran are:

(i) Rapid increases in population. Since 1990, due to the cultural, social and economic changes in Iran, there has been a rapid increase in population in such a way that during the past 50 years, the population has increased from 20 to 70million people, as demonstrated in Figure 3 (SCI,2005), much of which has settled in the major urban centers.

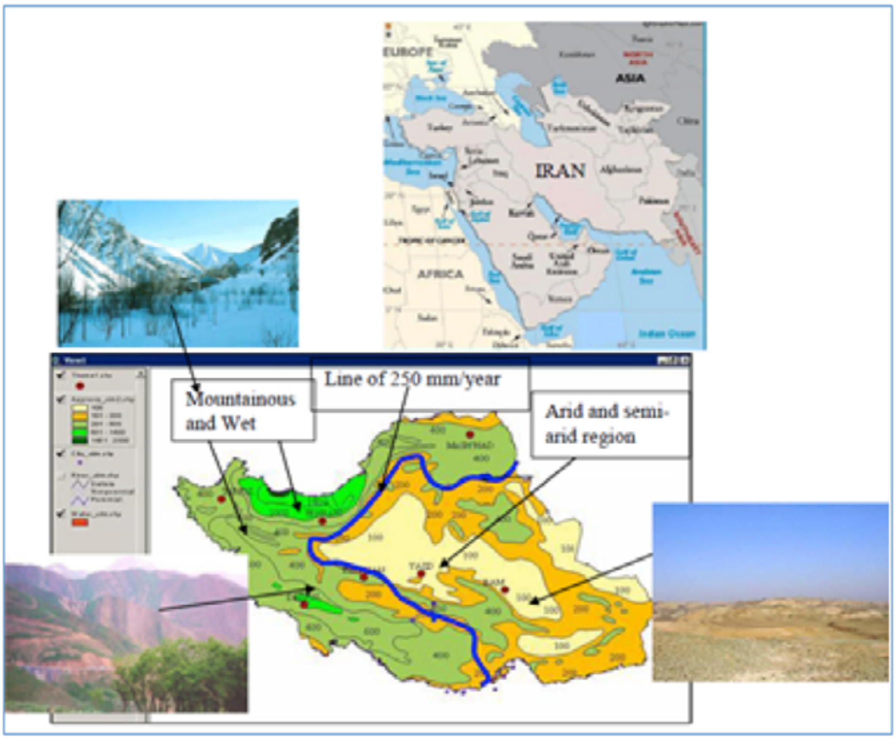

Figure 2- Geographic Location of Iran in Middle East and Annual Precipitation Map of Iran

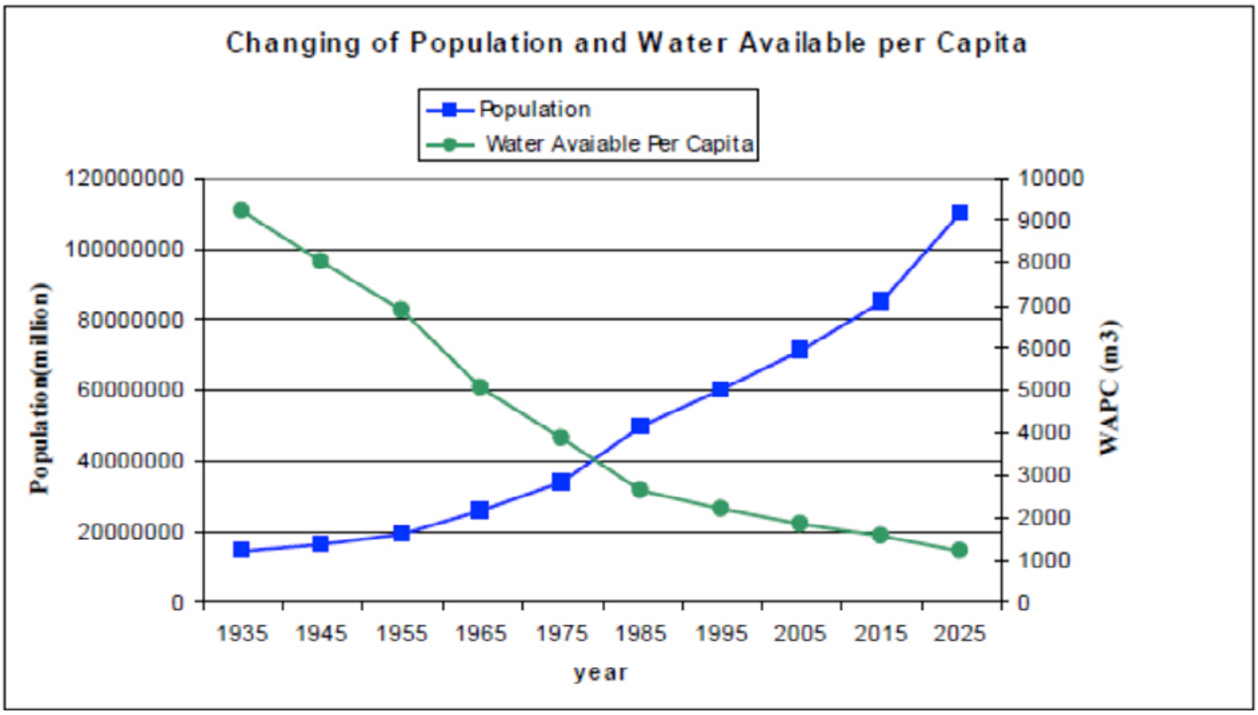

Figure 3- Population Increase in Iran (1935-2005) (SCI, 2005)

(ii) Occurrence of periodic droughts. Land degradation and desertification is one of the pressing challenges of Iran. About 85% of the area (approximately 39.4 million hectares out of 164.8 million ha) has been classified as arid and semi-arid, and receives between 30 to 250 mm of rainfall annually. An example of the impact of the drought and potential climate change is apparent on the lakes in central and southeastern parts of Iran. The Hamoun Lake in south eastern part of Iran is a dramatic case of a drying water body to a desert. Figure 4 shows the satellite images of the Hamoun Lake between 1997 and 2010 (Partov, 2003).

(iii) Development of different sectors in agriculture, industry and urbanization from 1990 to 2000 and still

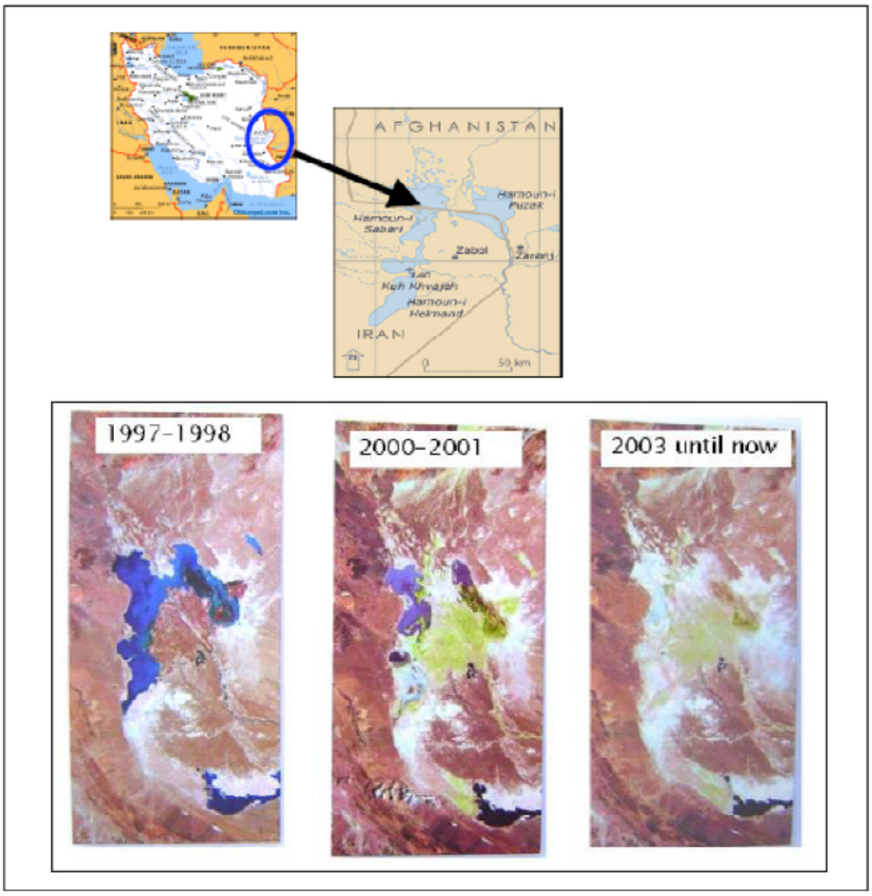

Figure 4- Location&the Satellite Pictures of the Hamoun Lake in Southeastern IranShowing The Dry out Progress Since 1997 Until the Present(Wikipedia).

until now. Water demand increased rapidly in different sectors in agriculture, industry and urban services. The increased water demand has been identified primarily with agriculture, where most water consumption and the highest losses occur, a fact which has been noticed by the Irrigation and Drainage Department (Javan et al., 2002).

(iv) Lack of proper water management, and consumption and over-withdrawal of groundwater resources. Drought, climate change, and desertification are some reasons of immigration; consequently, due to not having access to sufficient amount of water, widespread immigration to other regions occurred.

(v) Progress of desertification towards cities in the southeast. Construction and operation of hydraulic structures such as dams, qanats, conveyance channels for reservoirs, and transmission and distribution systems in Iran have been functioning for more than 3000 years (Motiee et al, 2006). The situation is now accepted that Iran is facing a water crisis and is in a serious situation to meet the necessary water demands. Based on existing reports the rate of the availability of water will drop from 1800 m^3/yr/cap.to 1000 m^3 /yr/cap.(Motiee et al., 2001).

FRESH WATER CONSUMPTION

At present Iran is using 60% of the total renewable freshwater while due to the international norms the upper limit should be 45% of renewable freshwater; it means that the remain unexploited renewable fresh water is only 15 % total fresh water resources including environmental basic needs.

GENERAL OVERVIEW OF WATER RESOURCES

Iran is divided into six following major hydrological basins as follows:

1. The Caspian Sea basin in the north, which consists of 7 sub basins,
2. The Lake Oroomieh basin in the northwest,
3. The Persian Gulf and Sea of Oman basin consists of 9 sub basins and extends from northwest up to southeast of country.
4. The central plateau basin, which has 9 subbasins, extends from northwest to southeast of the country and covers 5 dry Kavirs of which two (Lutand Central kavir) have nearly an area equal to 390000 km^2.

5. The Hamoun basin in the east with 3 sub-basins,
6. The Gharaghoum or Sarakhs basin in the northeast,

The internal renewable water resources of Iran are estimated at 130 cubic km per year. The surface runoff represents a total of 92 cubic km per year and ground water recharges is estimated at about 38 cubic km .The country also receives 6.7 cubic km per year of surface water from external source (mostly from Aras river in republic of Azerbaijan and Hirmand river of Afghanistan); while the surface runoff to the sea (Caspian, and Persian gulf and sea of Oman) and neighboring countries is estimated at 55.9 cubic km yearly. At present the per capita water resources of the country is 1380 cubic meters per year. In 1994 the total water consumption was 82 cubic km of which 92% have been used in agriculture, 6.5% in domestic and 1% industrial and mining activities. The total withdrawn of water in 1997 had been also 87 cubic km of which 94% was for agriculture, 5% for domestic and 1% in industrial and mining activities.

DROUGHT SITUATION IN IRAN

Due to climate change, common droughts in Asia and the Middle East have changed and the intensity and duration of these phenomena have increased. Today, it can be stated that drought is one of the horrible enemies in the Middle East which gradually causes water tables, current rivers, lakes and qanats disappearance.

In Iran during 2000-2010 the average rainfall of the country and the surface runoff has decreased 15% and 40% respectively and this has caused the government to develop water resources and to further investment to confront droughts.

As the average rainfall in Iran (250 mm/year) is one third of the global average and 90% of the country is located in an arid and semi-arid climatic condition, due to population increase and socio-economic development and finally droughts and climate change, water resources systems have faced increased pressure.

The mean water consumption per capita in the agricultural, industrial, potable and hygienic sectors (domestic) in developing countries is 30%, 59% and 11% respectively. This ratio in the less developed countries is 82%, 10% and 8% respectively while in Iran this ratio is 92%, 2% and 6% respectively.

The present droughts in Iran, particularly the ones happening in2008-2010 have completely imbalanced the country's climate. The decrease in rain fall and increase in temperature has caused many rivers, slumps and lakes to dry out. The utmost impact of this phenomenon could be observed in Oroomieh Lake which is further described in the next section. In this concern adaptation with the existing climatic situation should be made by appropriate consumption management and saving. The consumption pattern particularly in the agricultural sector should be defined, based on the country's climatic conditions. Apparently we can't make benefit of prescriptions used for the countries producing crops with plenty of water.

IMPACT ON LAKE OROOMIEH

Recent studies indicate there are substantial impacts of climate change and drought influencing water resources (e.g. IPCC, 2007).The consequence may include increases/decreases in hydrologic parameters, and adjustments in the frequency and magnitude of hydrologic extremes. For example, the circumstances of lakes around the world show that a significant number of lakes are experiencing decreasing water levels. Some lakes have dried out completely due to a combination of these changes plus mismanagement of water resources. A dramatic example is the Aral Sea (Figure 5), landlocked in Central Asia, with a drainage basin of 1.8 million km^2; due to mismanagement and drought, the water levels in the Aral Sea have decreased by 23 m (Micklin, 1992). This Sea is bordered by Kazakhstan in the north and Uzbekistan in the south.

In 1918, the Russian government decided to divert the Amu Darya and the Syr Darya, the two rivers that fed the Aral Sea, to irrigate areas of the desert. Unfortunately, many of the irrigation canals constructed in 1930s, were poorly built and allowed significant leakage and evaporation. By 1960, between 20to 50 km^3 of water was diverted each year to land, instead of to the Aral Sea and the Sea began to shrink. From 1961 to 1970, the Aral Sea's level fell at an average of 20cm a year and in the 1970s, the rate of water level decline nearly tripled to 50-60 cm per year. By the 1980s, the mean decrease was 80-90 cm annually (Bissell, 2002).

The water level in the Aral Sea has now decreased by 23 m. Its surface area has decreased by 74%, its volume, by 90%, and the salinity has increased from 10 to more than 100 g/L. The effects of these changes include: decimation of the native fish species, initiation of dust/salt storms, degradation of the deltaic biotic communities, and climate changes around the former shoreline. The population residing around the Sea has also been negatively impacted (Micklin, 1992).

Lake Oroomieh as another example in northwest of Iran with a surface of 5800 km2 is the second most saline lake in the world (the Red Sea is considered as the first), and is demonstrating significant declines in surface levels. In 2008, the depth of water in the Lake was measured to be two meters less than the long-term average and the volume is estimated to have decreased by one-third(McBean and Motiee,2009).

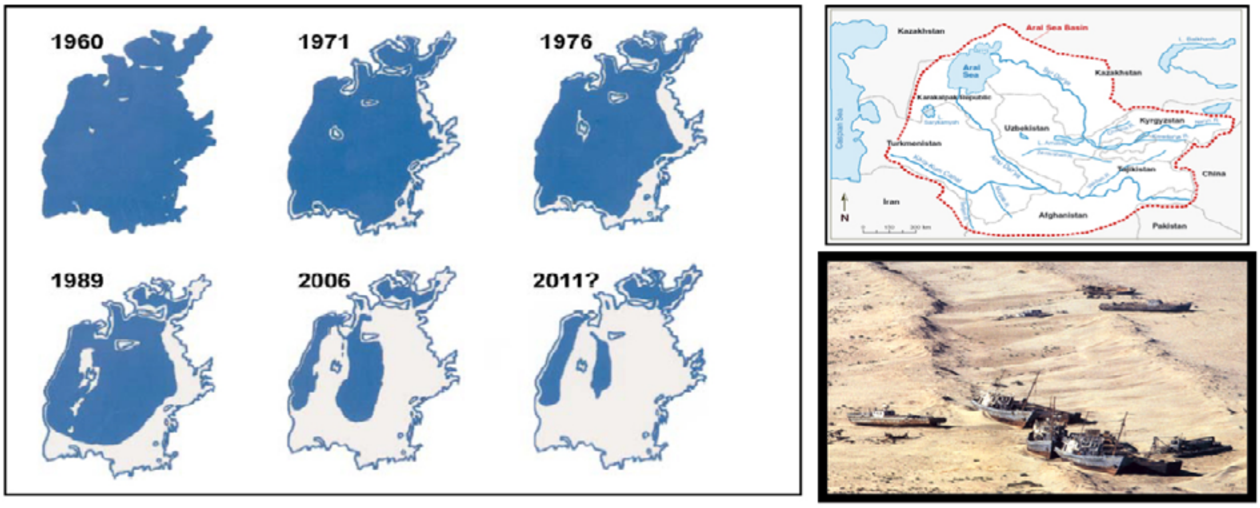

Figure 5- The geographical location of AralSea in the Middle Asia
and the trend towards dryness in the recent decades (mappery.com).

OROOMIEH LAKE SPECIFICATIONS

Oroomieh Lake is located in the north west of Iran. This lake is divided between east and west Azerbayejan. Lake Oroomieh is the biggest lake in Iran and the second salty lake in the world. The water basin of this lake is around 51876 km2 which is approximately 3% of the total area of the country. This basin by having large agricultural plains is one of the most important focal areas in agricultural and livestock activities in Iran. The normal capacity of this lake is over 30 Billion Cubic Meter (BCM).

Lake Oroomieh is one of the biggest permanent intakes in the west Asia and it is one of the most important natural habitants of the animals in Iran. At present there are 27 species of mammals, 212 bird species, 41 species of reptiles, 7 species of amphibian and 26 species of fish in this lake.

The water in Lake Oroomieh is so saline and it is mainly supplied by 6 rivers and the soluble salt is nearly two times as much as the oceans. Therefore no kind of fish or mollusca except crustacean live in this lake and the water never freezes. Swimmers can also swim on the water due to the high concentration of salts.

MAIN REASONS OF OROOMIEH LAKE DRY OUT

According to the measures made in 2010 and 2011, at present 1/3 of the lake surface has dried and been changed to salt marsh. The volume of this lake has reduced to 15 BCM which is less than half of the normal capacity. According to the recent photos, the water surface has dropped two meters below the normal depth. The increase in salt concentration is one of the negative results of this decline. The average salt concentration of this lake in long term was between150-170 gr./lit. while the present concentration of salt is 330 gr./lit. Figure 6 shows the lake water level fluctuation since 1995 which results in a considerable decrease in the depth of the lake.

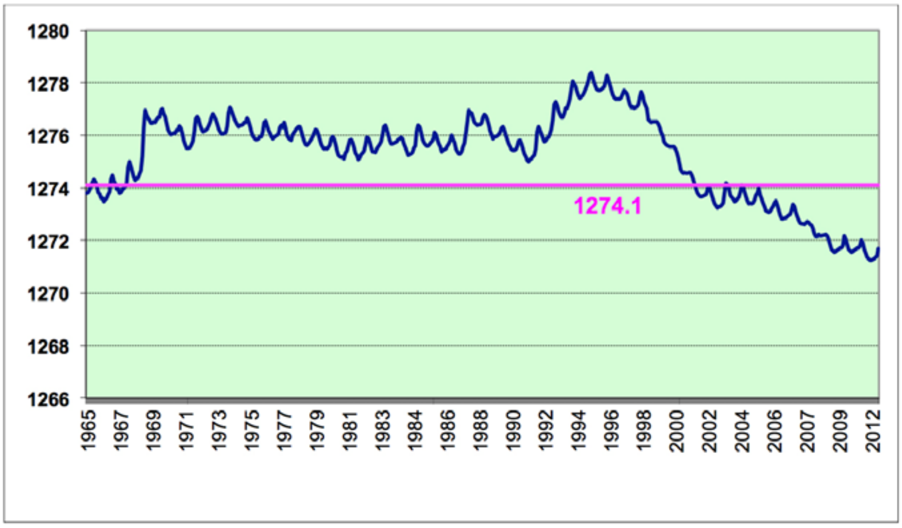

Figure 6: Lake Water level fluctuation

EFFECTIVE PARAMETERS IN DECREASING THE LAKE VOLUME.

The mainly uses and users of the water of this Lake are aqua life, tourist and environment.

A number of parameters have caused a part of Oroomieh Lake to dry out. 60% of it is related to drought and climate change factors and the rest is related to human parameters of which some are related to operation and others are related to the structures and dams controlling water. Water use in Agriculture and industry in the upstream areas of the lake have also had considerable impacts on the lakes volume decline.

One decade of continues drought (2000-2010) in the water basin of the lake has caused a severe reduction in the surface water of the basin towards the lake. According to the rainfall statistics during 2002-2005, 130 mm and during 2007-2010, 240 mm of rainfall decrease has been recorded in the water basin. Figure 7 demonstrates the shrinking process of the lake since 1995.

Climate change has had severe impacts on the water volume and depth of many lakes all around the world including the Oroomieh Lake. Global temperature increase of around 2 degrees Centigrade during the past 20 years, evaporation increase as well as rainfall decrease are all considered as the consequences of climate change. If this trend is continued, the destiny of this lake would be similar to the Aral Sea in the coming 2 decades.

The following figures (8, 9&10) demonstrate the rainfall, temperature and evaporation trend during the past 20 years respectively.

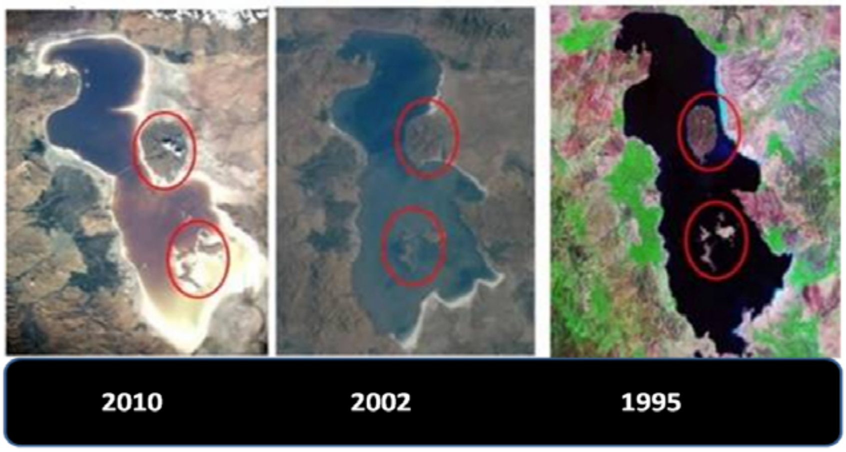

Figure 7- Gradual trend of the lake drying out from 1995 to 2010 with the use of satellite images (scoopweb.com)

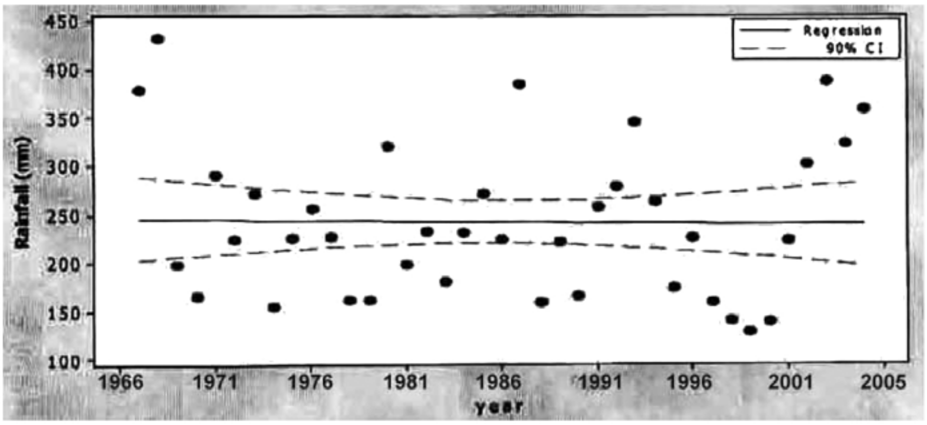

Figure8: Estimated Rainfall Height on Oroomieh Lake (Motiee, H., 2012)

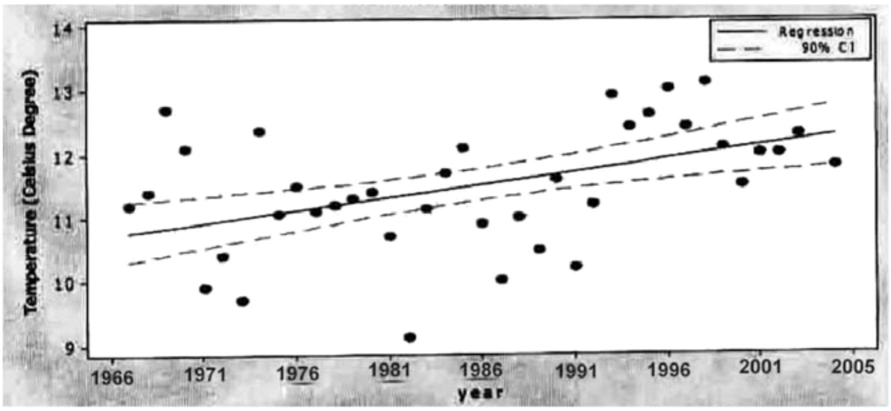

Figure 9: Trend of Temperature in Oroomieh basin (Motiee, H., 2012)

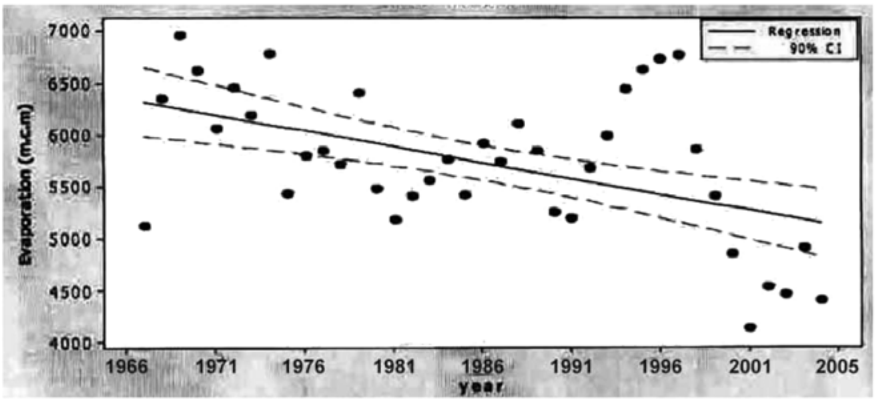

Figure 10: Volume of Actual Evaporation of Oroomieh Lake (Motiee, H., 2012)

ENVIRONMENTAL NEGATIVE IMPACTS

One of the damages is the bio-diversity impacts. Birds migrating to the region gave birth but their population is decreasing nowadays due to the high salinity of the lake water.

One of the other negative impacts which has caused the farmers anxiety is the salt which could be possibly spread throughout the region by wind after the lake has dried out. This can lead to soil salinity in the region. As the salt formations have a crystal shape this is just an unproved theory. Figure 11 displays the salt mass in the dried beach of the lake.

Figure 11- Salt crystals after the lake beach dry out (wdict.net).

INTERNATIONAL DROUGHT INITIATIVE (IDI)

In this part the International Drought Initiative proposed by the Islamic Republic of Iran to UNESCO which was later approved in the 19thIntergovernmental Council of UNESCO-IHP, is described. This initiative has been defined due to the high importance of drought in the world and the necessity for better relation and coordination amongst international organizations for knowledge and experience transfer.

Today's world, needs a global movement to face and encounter the challenges of natural disasters related to water, especially droughts, so that through systematic measures carried out by governments at national level and integrating them with the activities of international governmental and non-governmental organizations and entities, effective and coordinated action plans could be prepared. This global movement through mobilizing political wills and resources can create effective measures in order to predict and produce preparedness and mitigation plans at global scale.

Introducing the "International Drought Initiative" (IDI) can be a starting point and driving force for this global movement. In this draft concept paper, the objectives and framework for establishing and organizing such an initiative are presented in anticipation of further deliberations by experts and relevant entities.

AN OVERVIEW OF THE CURRENT SITUATION

With respect to drought management, different measures are carried out in various countries according to their level of development and lessons learnt on the impacts of past droughts. These measures have different aspects and dimensions. In developed countries, integrated plans are defined and executed and responsibilities are well divided. In developing or less developed countries which are much more vulnerable to droughts, no systematic and harmonized measures have been taken. In the latter countries, most of the measures carried out are concentrated after drought events, e.g. granting different helps and incomplete aids. International governmental and non-governmental entities also implement different programs and plans according to their functions and mission of which some concentrate on research, technical and practical assessments and some other on improvement of knowledge and awareness. Usually, at critical periods, some financial and logistic contributions will be provided for the affected regions by United Nations or affiliated entities.

With regards to the above mentioned matters, it can be concluded that the overall measures implemented at national and international levels don't have an organized and intelligent solidarity and coordination. Although, individual activities are so valuable and useful, a good use won't be made from the potential synergy of the set of these activities which can have an important effect and consequence in drought management.

IDI OBJECTIVES

According to the above-mentioned points and the necessity of strengthening communities to effectively face and encounter the consequences of this phenomenon, especially in developing and less developed countries, taking benefit of developed countries' experiences in this process and according to the contents of UN Convention to Combat Desertification (UNCCD) which emphasizes on compiling a drought preparedness plan, the International Drought Initiative would create an appropriate opportunity for a global movement related to different aspects of this phenomenon.

The methodology to prepare and compile policies and strategies related to drought management, the way to act in emergency situations, compiling practical plans to confront this phenomenon, clarifying stakeholder's participation, establishing warning systems, using networks to gather meteorological data, methodology of assessing damages and procedure for addressing environmental conflicts are among the issues that can be addressed in the framework of this initiative.

Role of the entities affiliated to UN and non-governmental organizations, and also countries in successfully compiling and executing drought management plans and their cooperation in achieving the goals is imperative and vital for successful implementation of this program. This program should be implemented to reduce the existing gap between developed and developing countries by utilizing valuable experiences and precise assessments of future needs. This program should also, guide the countries under coverage to follow acceptable standards in an appropriate time schedule by implementing necessary activities. It seems that this procedure will help to realize sustainable development and it contributes in mitigating the impacts of economical, social and environmental aspects of droughts in the coming decade of the 21st century. The objectives of the International Drought Initiative can be considered as follows:

1. Surveying the current situation of drought management in selected countries (or all countries) in different aspects such as: policy making, structural and non-structural plans;
2. Surveying the plans and measures of international and regional governmental/non-governmental entities involved in drought management;
3. Preparing and compiling the World Report on Drought Management (WRDM) in the current situation according to the outcomes of the two previous items and investigating the gaps and weak and strong points;
4. Executing necessary surveys to clarify needs and priorities of global measures in the framework of IDI;

5. Establishing the World Drought Watch (WDW) and Global Drought Preparedness Network (GDPM);
6. Helping different countries specially developing and less developed countries to prepare and compile strategic and practical drought management plans;
7. Develop and build capacities in: drought monitoring, mitigation, preparedness techniques and methodologies;
8. Holding international and regional conferences, seminars and workshops to exchange viewpoints, improve joint activities and exchange knowledge and experience related to different aspects of drought management;
9. Prepare and compile short-term, mid-term and long-term plans (perspective) for IDI and defining the indicators for assessing the progress made;

GOVERNANCE STRUCTURE OF IDI

As the success of IDI in realizing its goals depends on coordination and participation of interested countries as national and local governments function to design, implement, provide monitoring and evaluation of programs to deal with drought from one hand, and international and regional governmental / non-governmental entities from the other hand, the governance structure of this project should be set in such a way topractically encourage their participation in different steps from policy making to execution.

It is therefore suggested that a steering committee including representatives of some of the countries with valuable experiences in drought management as well as representatives of some of the international governmental entities such as: UNESCO-IHP, WMO, FAO, UNDP, GWP, WWC and ISDR be organized. This committee would be responsible for preparing and compiling the working procedures for the initiative in anticipation of its formal launch in late 2009.

The Regional Centre on Urban Water Management is prepared to organize the first meeting of the steering committee in the first quarter of 2009. According to the preliminary mutual understandings with UNESCO-IHP it was decided to carry out necessary investigations on the list of representatives of selected countries and also international and regional governmental / non-governmental organizations as the initial members of the steering committee. Upon finalizing the steering committee composition, formal invitations will be made by UNESCO.

It is worth mentioning that establishment of IDI as a global measure, has been highly received in some meetings related to water and supports have been made toward this suggestion.

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COMPUTATIONAL MODEL FOR ANALYSIS SPREAD IN FLOOD CHANNELS URBAN DRAINAGE

MODELO COMPUTACIONAL PARA EL ANÁLISIS DE LA PROPAGACIÓN DE LA INUNDACIÓN EN LOS CANALES DE DRENAJE URBANO

Stênio de Sousa Venâncio*
Luiz Fernando Resende dos Santos Anjo**

ABSTRACT

The scenario analysis for knowledge of the transitional system of urban macro drainage work is necessary for the planning of structural and nonstructural measurements. To this end, a computational model 1D is presented to study the flood propagation in urban drainage channels. This work investigates the unsteady flow in the Cocó River estuary, located in the city of Fortaleza-CE. It is one of the cases studied in the first author's graduate program, which proposes a computation model to simulate unsteady flows of open channels with many purposes (such as hydroelectric power, water supply, irrigation, etc.) and contributes to automation of their operational control systems . The determination of maximum water level achieved along the estuary is the aim of this study, having practical application on the definition of elevation of streets, avenues and new constructions to be executed on the border or inside the flood areas. The complete 1D hydrodynamic equations of Saint-Venant are approximated by a completely implicit method of finite differences and conveniently discretized for the model, which was developed in FORTRAN language. The flow given by the entrance hydrograph of the analyzed estuary (upstream boundary condition) was obtained for a return period of 50 years. The water depth is the boundary condition downstream of the problem, and its variation, obtained by measuring the tide in a 24 hour period, was approached by a mathematical function. This function was obtained for the purpose of measuring the maximum water level that occurs in the estuary. Was still considered to two lateral hydrographs and an inflow distributed along the estuary. The unsteady flow analysis is based on the temporal results of water level and flow at several cross sections of the estuary.
Keywords: urban flooding, macrodrainage, computational model.

RESUMEN

El análisis de escenarios para el conocimiento del sistema transitorio de obra de drenaje urbano macro son necesaria para la planificación de medidas estructurales y no estructurales. Con este fin, se presenta un modelo computacional 1D para estudiar la propagación de inundación en los canales de drenaje urbano. Este trabajo investiga el flujo transitorio en la desembocadura del río Cocó, ubicado en la ciudad de Fortaleza-CE. Es uno de los casos estudiados en el programa de posgrado del primer autor, que propone un modelo de computación para simular flujos inestables de canales abiertos con muchos propósitos (por ejemplo, energía hidroeléctrica, abastecimiento de agua, riego, etc.) y contribuye a la automatización de sus sistemas de control operacional. La determinación del nivel de agua máximo alcanzado a lo largo del estuario es el objetivo de este estudio, teniendo aplicación práctica en la definición de la elevación de las calles, avenidas y nuevas construcciones para ser ejecutado en la frontera de o dentro de las áreas de inundación. Las ecuaciones hidrodinámicas completa de 1D de Saint-Venant son aproximadas por un método totalmente implícito de diferencias finitas y discretizar convenientemente para el modelo, que fue desarrollado en lenguaje FORTRAN. El flujo dado por el hidrograma de entrada de la ría analizado (condición de frontera aguas arriba) se obtuvo para un periodo de retorno de 50 años. La profundidad del agua es la condición de frontera aguas abajo del problema, y su variación, obtenidos mediante la medición de la marea en un período de 24 horas, fue abordado por una función matemática. Esta función se obtuvo con el propósito de medir el nivel máximo de agua que se produce en el estuario. Todavía era considerado a dos hidrogramas laterales y una afluencia distribuidos a lo largo del estuario. El análisis de flujo transitorio se basa en los resultados temporales de flujo en varias secciones transversales de la ría y el nivel del agua.
Palabras clave: las inundaciones urbanas, macrodrenaje, modelo computacional.

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1. INTRODUCTION

The growth of cities was not accompanied by governing instruments for the soil use and occupation. As stated by CRUZ & TUCCI (2008):

> "According to IBGE (2000), considering 5.507 Brazilian municipalities, only 841 have Urban Master Plans (PDU) (15.3%), and of these, only 489 in the latest version of the plan are later than 1990 (8.9%). When analyzing only those cities with population exceeding 20,000 inhabitants, 485 have PDU from a total of 1483 municipalities (32.7%). Even where there are PDUs, most of these plans only deal with architectural aspects, without considering environmental effects and especially on **the drainage infrastructure**. Within the urban practices that have spread across the country, the use of valleys avenues associated with the plumbing of urban streams was observed. This sort of urbanization amplifies the impacts and changes the environment in an inappropriate way. Solutions of this type generally have a cost much higher than a sustainable solution and increased losses due to flooding, erosion and water quality. The sum of technical ignorance of an important part of professionals working on drainage, population and policy makers have kept this scene."

Changing this setting requires changing the strategic pattern of the city integrated planning and it involves: urban planning and soil use, sanitation, solid waste and urban drainage. All these elements have strong interference with each other and require integrated solutions.

All this dynamic and the increased frequency of floods in recent decades have become increasingly important to incorporate tools to help the decision making process in the management of urban drainage.

The change in rainfall patterns, widely treated by the media on the issue of global climate change, is an aggravating factor in the secure management of urban infrastructure in terms of flooding, with additional impact on the coastal cities where the tide cycle is decisive in determining timing of water levels in the drainage channel.

According to Mark et al. (2004), with the current advances in computer technology, many cities in developed countries use computer simulations to solve their local problems of flooding. The practice involves building models of drainage systems using applications such as MOUSE (Abbott et al., 1982, Lindberg & Jørgensen, 1986), SOBEK-Urban (Heeringen et al., 2002), InfoWorks CS (Chan & Vass, 2002) and SWMM (Huber & Dickinson, 1992). Based on simulation results, mitigation measures can be evaluated and the optimal solution can be implemented. The main caveat with regard to commercial software packages is in the restriction of access to source code, which complicates the understanding of certain types of errors, besides many of them do not include important parameters in the analysis process, or are not used properly by users. One of these parameters is sediment transport, whose effect impact in reducing flow capacity of the urban drainage channels. Some conclusions about the hydrosedimentological simulation are presented at the end, from the literature review by Venâncio (2009). The description of the item 2.2 (Numerical Model) is presented in Venâncio, Sousa and; Villela (2005).

2. METHODOLOGY.

2.1 Study Area.

The Rio Coco is part of the basin of the rivers in the east coast of Ceará, with its catchment area of approximately 485 km ², with a total length of the main river about 50 km (SEMACE, 2012). The river runs through the municipalities of Pacatuba, Maracanaú and Fortaleza, and its source is situated on the eastern slope of the Sierra Aratanha. Its mouth is on the edge of the beaches of Hunting and Fishing and Sabiaguaba, thus emptying into the Atlantic Ocean. The Coco River Basin is considered the largest river in the city of Fortaleza, it has 25 km of its length in the capital.

The area chosen for analysis in question is the entire area that is related to influence Coco River estuary, and comprises approximately 15 km of the length of the river from its mouth upstream, within the limits of the city of Fortaleza (Figure 1). The portion of the river, which is the state capital of Ceará, has mangrove ecosystem associated with fluvial-marine plain, which occupies the excerpts from the river located on BR-116 to its mouth, where it forms an estuary.

These areas due to favorable conditions such as mixing of saline water with fresh water, soil type, low coefficients of oxygen in the soil (ie, reducing environment) and tidal regimes, the dominant species are Rhizophora mangle L, Avicenia Schaveriana Stapf and Leech, and Laguncularia racemosa (SEMACE, 2012).

Natural environments are subject Cocó intensely human activity that intervenes significantly through constructions of households, urban roads, public facilities and commercial developments. These urban facilities directly interfere in sedimentary processes, morphological, ecological and oceanographic region. Historically, since 1933 the Estuary Coco concentrated low-income housing, and currently has a number of environmental and social problems arising from lack of urban planning, mainly due to population growth and inadequate implementation of structural designs, such as sanitation basic fluvial drainage works, construction of affordable housing and other forms of occupation (RGP, 2009).

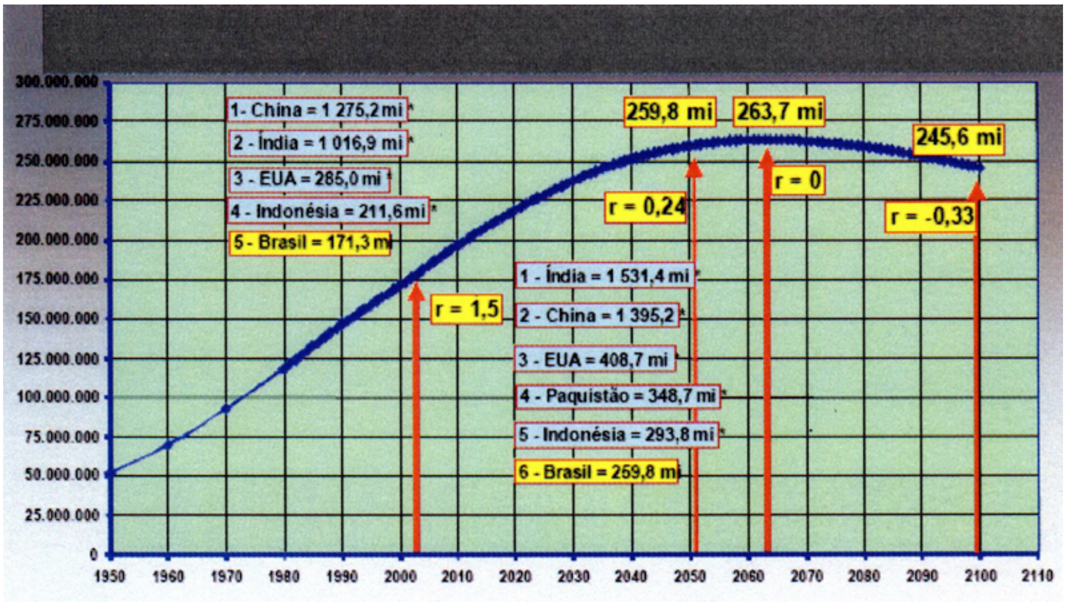

Figure 1. Location of the study area in Fortaleza/CE.

Even being inserted in the semi-arid climate, its location change this reality by being among nearby hills causing summer rains occur more often in the city and surrounding area than in the rest of the state. The average annual temperature is 26° C. The average rainfall is about 1600 mm. Without the seasons well defined, there is only the rainy season, from January to July and the dry from August to December. With most of the sandy soil agriculture becomes of little economic significance, and since the 1990 the entire length of the city was considered urban area (WIKIPEDIA, 2013).

The average flow in the estuary, in steady state, is 10 m^3/s, obtained by measuring station river. The monitoring of historical rainfall data and qualitative and quantitative water resources of the Basin estuarine Coco are managed by the COGERH (Company Water Resources Management) from the state government of Ceará.

2.2 Numerical Model

The mathematical model conceptual employed to study the free flow in the transient regime with bidirectional flow, is set out in the literature, for validations generated in various applications. It is composed of the hydrodynamic equations completes, Continuity and amount movement, known as the Saint-Venant equations.

2.2.1 Governing Equations

The continuity equation follows the way presented by Henderson (1966):

$$\frac{\partial y}{\partial t} + \frac{1}{B}\frac{\partial Q}{\partial x} \pm \frac{q_{LAT}}{B} = 0 \qquad (1)$$

where ∂y/∂t is the rate of temporal variation of water height considering the bottom of the channel; ∂Q/∂x rate of spatial variation of flow, B the width of the free surface, and q_{LAT} the intake of side flow in meters from the banks. From the relation ∂y/∂t = ∂h/∂t - ∂z/∂t, where ∂h/∂t is the variation of water height relative to a horizontal reference plane at the considered time and ∂z/∂t = 0 (once the bottom slope does not vary with time), the general equation can be rewritten as:

$$\frac{\partial h}{\partial t} + \frac{1}{B}\frac{\partial Q}{\partial x} \pm \frac{q_{LAT}}{B} = 0 \qquad (2)$$

The equation of movement amount is given as follows:

$$S_f - S_0 + \frac{\partial y}{\partial x} + \frac{V}{g}\frac{\partial V}{\partial x} + \frac{1}{g}\frac{\partial V}{\partial t} = 0 \qquad (3)$$

where S_f is the slope of the power line; S_0 to the channel bottom slope; ∂y/∂x the rate of spatial variation of water depth; ∂V/∂x rate of spatial variation of mean flow velocity; ∂V/∂t the rate of temporal variation of mean velocity and g is the acceleration of gravity. Substituting S_0 by ± ∂z/∂x and S_f by $V^2/C_H^2.R_H = Q^2/A^2.C_H^2.R_H$ in Eq. (3), it can be written as:

$$\frac{Q^2}{A^2 C_H^2 R_H} \pm \frac{\partial z}{\partial x} + \frac{\partial y}{\partial x} + \frac{V}{g}\frac{\partial V}{\partial x} + \frac{1}{g}\frac{\partial V}{\partial t} = 0 \qquad (4)$$

where A is the cross-sectional area, and R_H is the hydraulic radius of the section, and C_H the Chezzy coefficient, a function of hydraulic radius and Manning roughness coefficient ($C_H=R_H1/6/n$) determined for each step of time of the established discretization. Introducing the relation ± ∂z/∂t = ∂h/∂x - ∂y/∂x in Eq. (4) and multiplying it by g.A^2, it becomes:

$$\frac{\partial Q}{\partial t}A + Q\frac{\partial Q}{\partial x} + \frac{g}{C_H^2 R_H}Q|Q| + gA^2\frac{\partial h}{\partial x} = 0 \qquad (5)$$

2.2.2 Discretization

One of the most used schemes for the variable flow analysis in channels is the implicit finite difference scheme by Preissmann (apud LIGGET and CUNGE 1975), given by:

$$\frac{\partial f}{\partial t} = \frac{1}{\Delta t}\left[\phi\left(f_{i+1}^{k+1} - f_{i+1}^{k}\right) + (1-\phi)\left(f_i^{k+1} - f_i^{k}\right)\right]$$

$$\frac{\partial f}{\partial x} = \frac{1}{\Delta x}\left[\theta\left(f_{i+1}^{k+1} - f_{i}^{k+1}\right) + (1-\theta)\left(f_{i+1}^{k} - f_i^{k}\right)\right] \qquad (6)$$

θ and ϕ are weighting factors which, for ϕ = 0,5 e θ = 1 a fully implicit scheme considered by Preissmann is presented as follows:

$$\frac{\partial f}{\partial t} = \frac{1}{2}\left[\frac{\left(f_{i+1}^{K+1} - f_{i+1}^{K}\right)}{\Delta t} + \frac{\left(f_i^{K+1} - f_i^{K}\right)}{\Delta t}\right]$$

and $$\frac{\partial f}{\partial x} = \frac{f_{i+1}^{K+1} - f_i^{K+1}}{\Delta x} \qquad (7)$$

where the average of the variable f is calculated by

$\bar{f} = \frac{f_{i+1}^{K} + f_i^{K}}{2}$, which i would represent the sections, k the calculation time and f the representative value of any variable of the problem where, for the presented case is given by Q (m^3 / s) and h (m) .

Discretizing the continuity equation Eq. (2) for this scheme, it follows

$$\frac{1}{2}\left[\frac{h_{i+1}^{k+1} - h_{i+1}^{k}}{\Delta t} + \frac{h_i^{k+1} - h_i^{k}}{\Delta t}\right] + \frac{1}{\bar{B}}\left[\frac{Q_{i+1}^{k+1} - Q_i^{k+1}}{\Delta x}\right] \pm \frac{q_{LAT}}{\bar{B}} = 0 \qquad (8)$$

which is multiplied by 2Δ*t* and it is

$$h_{i+1}^{k+1} - h_{i+1}^{k} + h_i^{k+1} - h_i^{k} + \frac{2\Delta t}{\Delta x}\frac{1}{\bar{B}}\left(Q_{i+1}^{k+1} - Q_i^{k+1}\right) \pm 2\Delta t\frac{q_{LAT}}{\bar{B}} = 0 \qquad (9)$$

Defining $\frac{2\Delta t}{\Delta x}$ as α and rearranging Eq. (9) in terms of K and K +1, you can write it as

$$h_{i+1}^{k+1} + h_i^{k+1} + \frac{\alpha}{\bar{B}}Q_{i+1}^{k+1} - \frac{\alpha}{\bar{B}}Q_i^{k+1} = h_i^{k} + h_{i+1}^{k} \pm 2\Delta t\frac{q_{LAT}}{\bar{B}} \qquad (10)$$

As $h_{i+1}^{k} + h_i^{k} = 2\bar{h}$ the Eq. (10) is

$$-\frac{\alpha}{\bar{B}}Q_i^{k+1} + h_i^{k+1} + \frac{\alpha}{\bar{B}}Q_{i+1}^{k+1} + h_{i+1}^{k+1} = 2\bar{h} \pm 2\Delta t\frac{q_{LAT}}{\bar{B}} \qquad (11)$$

Therefore

$$A_J = -\frac{\alpha}{\bar{B}}\,;\ B_J = 1\,;\ C_J = \frac{\alpha}{\bar{B}}\,;\ D_J = 1\,;\ E_J = 2\bar{h} + 2\Delta t\frac{q_{LAT}}{\bar{B}}$$

(for side flow input), and $E_J = 2\bar{h} - 2\Delta t\frac{q_{LAT}}{\bar{B}}$

(for side flow output), reminding that if there is no entry and exit of side flow, the term E$_J$ becomes $E_J = 2\bar{h}$ the discrete equation of continuity is the following

$$A_J V_i^{k+1} + B_J h_i^{k+1} + C_J V_{i+1}^{k+1} + D_J h_{i+1}^{k+1} = E_J \qquad (12)$$

Applying the approximation scheme for the movement amount equation Eq. (5) and following the same steps taken earlier, it is

$$\left(1 - \alpha\frac{\bar{Q}}{\bar{A}} + \frac{g\Delta t|\bar{Q}|}{\bar{A}\bar{C}_H^2\bar{R}_H}\right)Q_i^{k+1} - \alpha g\bar{A}h_i^{k+1} +$$

$$\left(1 + \alpha\frac{\bar{Q}}{\bar{A}} + \frac{g\Delta t|\bar{Q}|}{\bar{A}\bar{C}_H^2\bar{R}_H}\right)Q_{i+1}^{k+1} + \alpha g\bar{A}h_{i+1}^{k+1} = 2\bar{Q} \qquad (13)$$

with $\bar{Q} = \frac{Q_{i+1}^{k} + Q_i^{k}}{2}$ and $Q_{i+1}^{k} + Q_i^{k} = 2\bar{Q}$.

Reducing the terms of the equation for

$$A_{JL} = \left(1 - \alpha \frac{\overline{Q}}{\overline{A}} + \frac{g\Delta t\left|\overline{Q}\right|}{\overline{A}\overline{C}_H^2\,\overline{R}_H} \right);\ B_{JL} = -\alpha g\,\overline{A};\ C_{JL} = \left(1 + \alpha \frac{\overline{Q}}{\overline{A}} + \frac{g\Delta t\left|\overline{Q}\right|}{\overline{A}\overline{C}_H^2\,\overline{R}_H} \right);\ D_{JL} = \alpha g\,\overline{A} \text{ e } E_{JL} = 2\,\overline{Q}$$

the equation of movement is treated as

$$A_{JL}Q_i^{k+1} + B_{JL}h_i^{k+1} + C_{JL}Q_{i+1}^{k+1} + D_{JL}h_{i+1}^{k+1} = E_{JL} \quad (14)$$

3. APLICATION

The studied estuary was spatially discretized into 32 sections (N_Z = 32 sections), listed from upstream to downstream, with a total length L = 15.500m. The boundary conditions of the problem are the upstream input hydrograph and downstream tide equation. Two side hydrographs are still considered. The outline of the problem is shown in Figure 1 below.

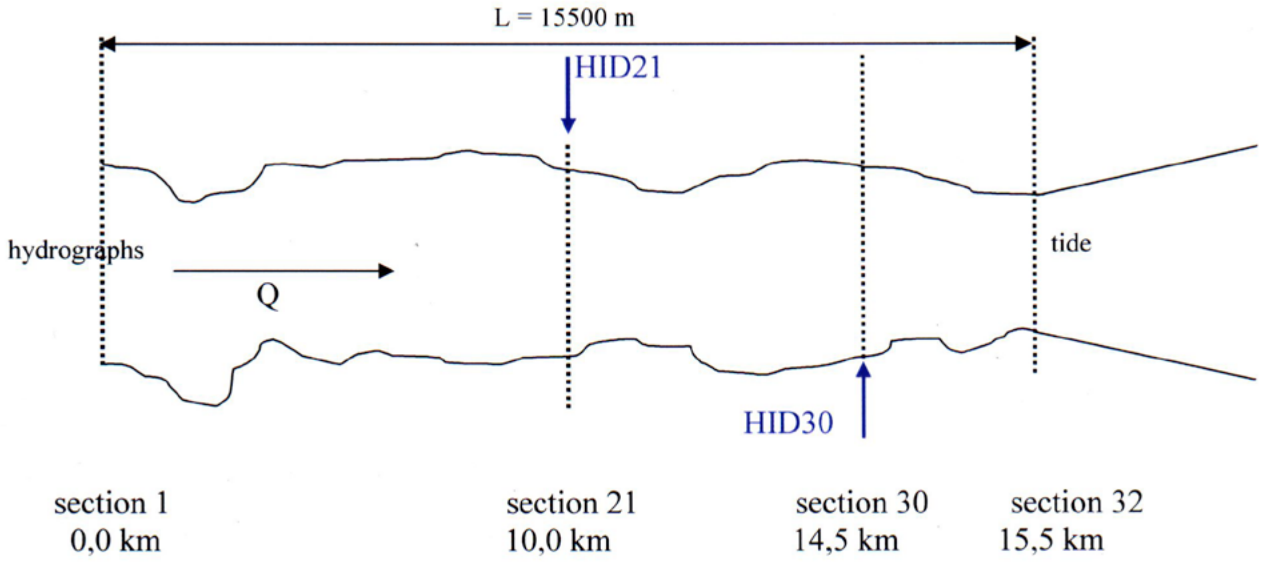

Figure 2 - The Cocó River estuary Scheme to the application of the model, with HID21 and HID30 representing the two side hydrographs.

For the discretized mathematical equations above, the following linear system occurs:

$$\begin{aligned}
&A_{J1}Q_1^{K+1} + B_{J1}h_1^{K+1} + C_{J1}Q_2^{K+1} + D_{J1}h_2^{K+1} = E_{J1}\\
&A_{JL1}Q_1^{K+1} + B_{JL1}h_1^{K+1} + C_{JL1}Q_2^{K+1} + D_{JL1}h_2^{K+1} = E_{JL1}\\
&A_{J2}Q_2^{K+1} + B_{J2}h_2^{K+1} + C_{J2}Q_3^{K+1} + D_{J2}h_3^{K+1} = E_{J2}\\
&A_{JL2}Q_2^{K+1} + B_{JL2}h_2^{K+1} + C_{JL2}Q_3^{K+1} + D_{JL2}h_3^{K+1} = E_{JL2}\\
&\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\\
&\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\\
&A_{J31}Q_{31}^{K+1} + B_{J31}h_{31}^{K+1} + C_{J31}Q_{32}^{K+1} + D_{J31}h_{32}^{K+1} = E_{J31}\\
&A_{JL31}Q_{31}^{K+1} + B_{JL31}h_{31}^{K+1} + C_{JL31}Q_{32}^{K+1} + D_{JL31}h_{32}^{K+1} = E_{JL31} \quad (15)
\end{aligned}$$

where the overwritten index of Q and h represent the time of calculation, and the subscribed index represent the considered sections. The values A, B, C, D and E are determined by expressions previously developed in an explicit way. Thus we can conclude that for N_Z = n sections, the system consisted of 2.(*n*-1) = *equations* and 2.*n*= *unknowns* what in this case represents a number of 62 equations and 64 unknowns. Introducing the boundary system, this becomes:

$$
\begin{array}{l}
h_1 = F_1 \\
A_{J1}Q_1^{K+1} + B_{J1}h_1^{K+1} + C_{J1}Q_2^{K+1} + D_{J1}h_2^{K+1} = E_{J1} \\
A_{JL1}Q_1^{K+1} + B_{JL1}h_1^{K+1} + C_{JL1}Q_2^{K+1} + D_{JL1}h_2^{K+1} = E_{JL1} \\
A_{J2}Q_2^{K+1} + B_{J2}h_2^{K+1} + C_{J2}Q_3^{K+1} + D_{J2}h_3^{K+1} = E_{J2} \\
A_{JL2}Q_2^{K+1} + B_{JL2}h_2^{K+1} + C_{JL2}Q_3^{K+1} + D_{JL2}h_3^{K+1} = E_{JL2} \\
\cdots\cdots\cdots\cdots\cdots\cdots \\
\qquad\qquad\updownarrow \\
\cdots\cdots\cdots\cdots\cdots\cdots \\
A_{J31}Q_{31}^{K+1} + B_{J31}h_{31}^{K+1} + C_{J31}Q_{32}^{K+1} + D_{J31}h_{32}^{K+1} = E_{J31} \\
A_{JL31}Q_{31}^{K+1} + B_{JL31}h_{31}^{K+1} + C_{JL31}Q_{32}^{K+1} + D_{JL31}h_{32}^{K+1} = E_{JL31} \\
Q_{32} = F_{32}
\end{array}
\qquad (16)
$$

and therefore a system with 64 equations and 64 unknowns. $F_1 = h_1$ is obtained by downstream tide equation as follows:

$$F_1 = h_1 = h_{\text{MARÉ}} = y_{\text{inic}} + A\,\text{sen}\left[\left(\frac{2\Pi}{T}\right)t\right] + z_1 \qquad (17)$$

Where:

yinic = 1.00 m = initial height of the tide in section 1 (when.t = 0h); A = 1.60 m = height of the tide; Π = 3.141592654; T = 12 H = period of the tide; z_1 = share of the channel bottom in section 1; t = time of computation in hours; $F_{32} = Q_{32}$, is the upstream boundary condition attributed directly to the characteristic hydrograph of the estuary.

To solve the system, are given further: Qi = 10.00 m3 / s = initial flow in the channel; g = 9.81 m/s2 = acceleration of gravity; z = 500 m = spacing between sections; Dt = 3600 s = time interval of calculation; Nt = 6 = number of time intervals for calculating; q_{LAT} = 0.0001 m3/sm = lateral contribution; n = 0.035 = Manning coefficient; Nz = 32 = number of discrete sections; HID21 = side hydrograph in section 21; HID30 = side hydrograph in section 30; ALT = initial height of water, obtained by the energy equation via Step Method; QUOTA = bottom of the channel quota obtained topographically.

The system of equations is then prepared in a matrix, according to Fortuna (2000), expressed as in Figure 3, to be solved numerically. The Matrix A and vector B are explicitly calculated in time K and the vector U obtained implicitly by solving the system at time K+1.

3.1 Computational Model

With the aim of implementing the simulation of transient flow in open channels, with discretization of the Saint-Venant 1D equations through the scheme implicit by Preissmann, a computer model in FORTRAN language was developed. The model applied in this study can be extended to other cases making adjustments in geometry, boundary conditions, temporal and spatial discretization. In cases of natural channels, the approach must be careful, because the geometry of the sections is approximated by mathematical functions that may exhibit divergence in the limits of maximum and minimum water depth. The block diagram of the model is shown in figure 4.

$$
\overset{\textbf{Matrix A}}{\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
B_{J1} & A_{J1} & D_{J1} & C_{J1} & 0 & 0 & 0 & 0 & 0 & 0 \\
B_{JL1} & A_{JL1} & D_{JL1} & C_{JL1} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & B_{J2} & A_{J2} & D_{J2} & C_{J2} & 0 & 0 & 0 & 0 \\
0 & 0 & B_{JL2} & A_{JL2} & D_{JL2} & C_{JL2} & 0 & 0 & 0 & 0 \\
- & - & - & - & - & - & - & - & - & - \\
- & - & - & - & - & - & - & - & - & - \\
0 & 0 & 0 & 0 & 0 & 0 & B_{J31} & A_{J31} & D_{J31} & C_{J31} \\
0 & 0 & 0 & 0 & 0 & 0 & B_{JL31} & A_{JL31} & D_{JL31} & C_{JL31} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}}
*
\overset{\textbf{Vetor U}}{\begin{bmatrix}
h_1 \\ Q_1 \\ h_2 \\ Q_2 \\ h_3 \\ - \\ - \\ Q_{31} \\ h_{32} \\ Q_{32}
\end{bmatrix}}
=
\overset{\textbf{Vetor B}}{\begin{bmatrix}
F_1 \\ E_{J1} \\ E_{JL1} \\ E_{J2} \\ E_{JL2} \\ - \\ - \\ E_{J31} \\ E_{JL32} \\ F_{32}
\end{bmatrix}}
$$

Figure 3 – Matrix of the equations used for the numeric solution.

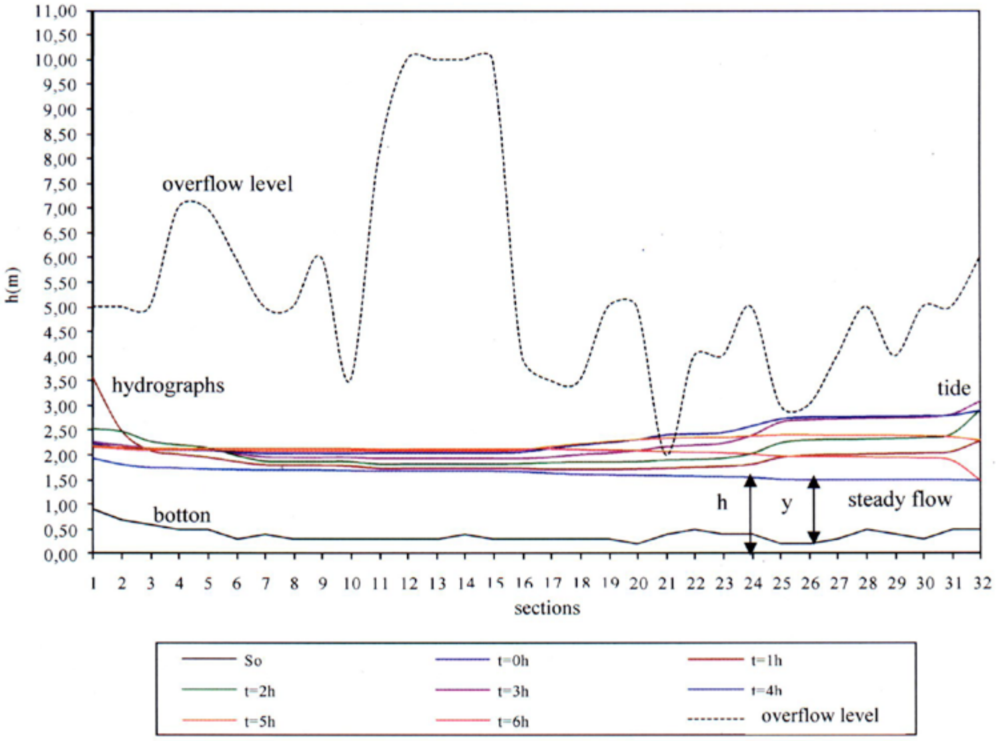

Figure 4 – Block Diagram of the Model.

4. RESULTS

The height of water data, flow and speed in function of time are summarized in Figures 5, 6 and 7 for the discretized sections of the estuary. The initial time t = 0 h was considered when the estuary is at steady state. The time steps are in a period of 1min in a simulated total period of 6 hours. Figure 5 shows the evolution of water height with time along the estuary, with a predominance of the tide on the amount of flow between sections 16 and 32. The maximum height occurs within the first 2 hours for the sections between 1 and 5 due to the influence of the hydrograph peak. For other sections the maximum is reached in the third hour, depending on the maximum height of the tide. The overflow observed in section 21 is an important detail of the simulation, because it corresponds to a characteristic point of flooding.

Figure 6 shows the propagation of the downstream flow (characterized by the rising tide into the estuary) the time of 3h, when its height is maximum . After a period of three hours the tide begins to go down, freeing the flow of the accumulated amount flow in the period. The flow then tends to steady state, with positive values along the estuary, i.e., with the predominance of the amount flow.

The graph in Figure 7 shows the peak level reached in the various sections of the estuary in the simulated period, expressing clearly the sector where flooding occurs (section 21).

Hydraulic changes occurring in the estuary, during periods of high and low tide, are equivalent to the results of work carried out for the same purpose (variation of water levels in the estuary), where the main bottleneck is the unavailability of field data to feed calibration of the model. As an example of equivalent studies can be cited: Como exemplo de estudos equivalentes pode ser citado: Pinho (2005); Stoschek e Zimmermann (2006); Kwnow, Maa e Lee (2007); Ganju e Schoellhamer (2009) and Hu et al. (2009).

6. CONCLUSIONS

This computer model simulation performed for the conditions of the drainage channel, estuarine stretch of the River Coco within a period of 6 hours, with the determination of maximum levels in the estuary. These levels served as parameters for interventions in the areas adjacent to the estuary for urbanization purposes. Therefore, the main objective was achieved.

For the application of the computational model presented in this study in other cases, even with no estuary, there must be an adaptation to the specific geometric and hydraulic situation addressed, as well as boundary conditions of the particular problem. It is also important to note that the computational model implemented here was motivated by the need to serve a practical purpose and, therefore, it is limited to only simulate the occurrence of peak levels.

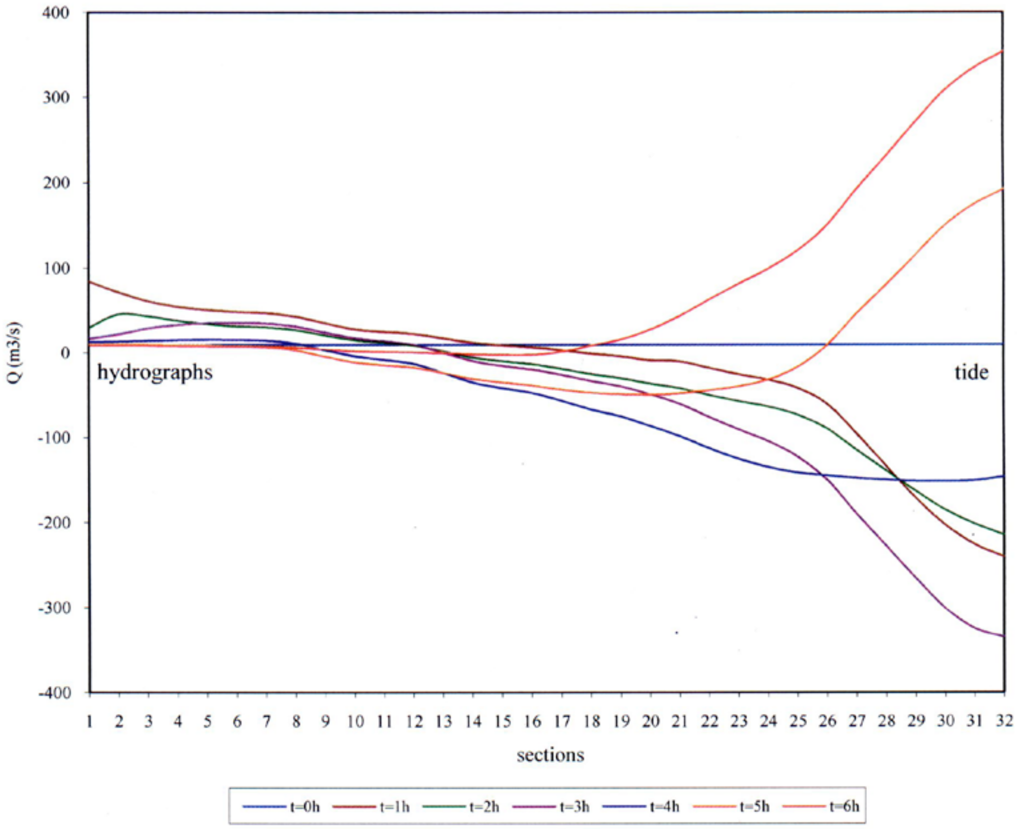

Figura 5 - Evolution of water height in time.

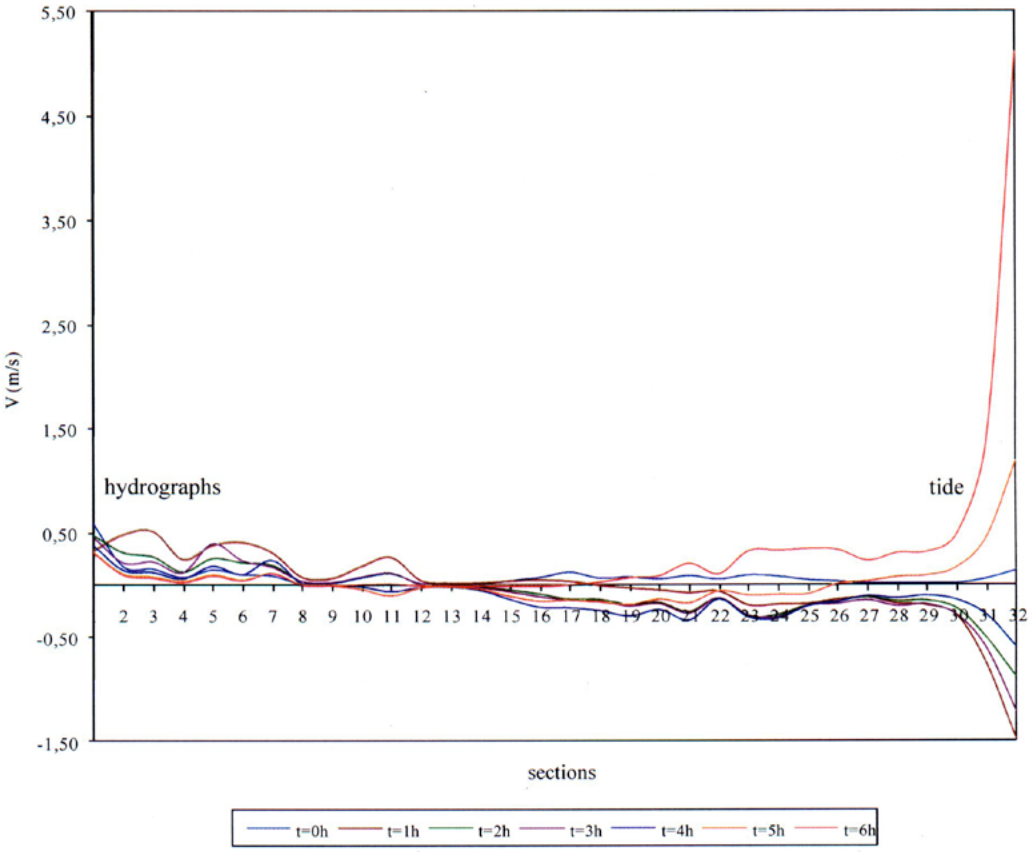

Figura 6 - Evolution of the flow in time.

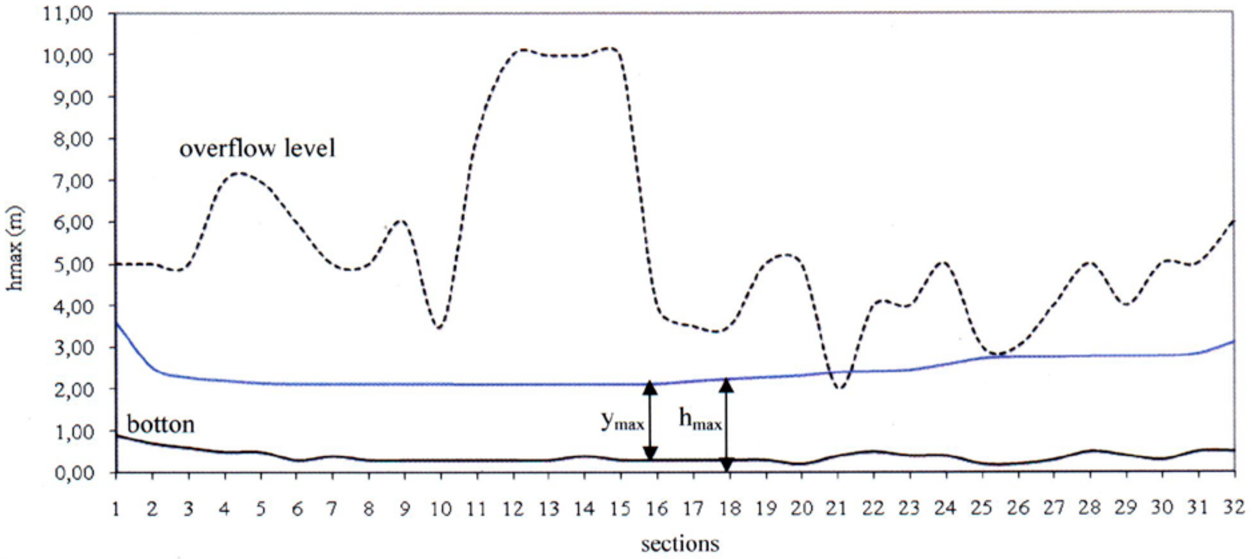

Figura 7 - Maximum level of water in the estuary.

This limitation is imposed by the tidal equation which does not reproduce the minimum heights.

Despite the actual phenomenon is reproduced in the same order of magnitude (of space and time) the validation of this simulation is subject to making measurements of water height in the channel during the rise of the tide. These field data, not available to carry out this simulation, would allow the calibration of the model and check its efficiency.

In the case of natural channels (not prismatic sections), it is worth noting that care must be taken as the geometric aspect. As the geometric configuration of the sections are approximated by mathematical functions (A = f (y)) and P = f (y)), the correlation obtained should be analyzed carefully for the maximum and minimum heights reached in the simulation of water, avoiding to numerical instabilities. The next step of this work is the validation with the consequent inclusion of sediment transport module. The major deadlock in this type of modeling, based on previous work is the unavailability of field data, no contemplation of important parameters for numerical models (winds, turbulence, temperature, etc.) and empirical mathematical modeling with results showing significant errors. Not less important is the necessary qualification for the collection and interpretation of data and appropriate use of model for each situation. All this reality justifies the continuation of studies in this direction, pointing to computational programs with open source codes, which facilitate the interpretation of errors in the results and relevant adjustments, which do not happen with commercial software because of the so-called “black boxes”. Without intending to model the nature accurately, the computational tool provides more efficient and integrated actions from the quantification of transient phenomenon in the drainage channels.

Finally, the availability of data for field calibration and validation extensive computational time for the adjustment and sensitivity analysis of the data and also the limitations of templates to cover certain data types, or to consider them as appropriate, make process of numerical simulation results that hard to not always represent accuracy.

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GIS APPLICATION IN FLOOD MANAGEMENT – A CASE STUDY: PARAIBA DO SUL BASIN, SOUTHEAST BRAZIL

UTILIZACIÓN DE GIS EN EL MANEJO DE INUNDACIONES – CASO DE ESTUDIO: CUENCA DE PARAÍBA DEL SUR, SUDESTE DE BRASIL

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Isabel Cristina de Barros Trannin[3]

Abstract

In different regions of Brazil, floods have increased dramatically, affecting millions of people and inflicting huge economical damage. Flood hazard maps are important to integrate geospatial and temporal data in a same computational environment that allows risk assessment, modeling and decision support. This paper discusses different levels of integration approaches between GIS and hydrological models and presents a case study,in which all the tasks of creating model input, editing data, running the model, and displaying output results are available withina GIS. The study area corresponds to the upper section of the Paraíba do Sul basin (Sao Paulo State portion), comprising nearly 15,300 km2 and situated in the Southeast of Brazil. Paraiba do Sul basin has a large importance in the history, culture and economy of Brazil with high urbanization and industrial activities along a part of the main river. The case study presented in this paper has a database which is suitable for the basin dimension including digitized topographic maps. From ArcGIS®/ArcHydro Data Modela geometric network called HydroNetwork was created to produce different raster maps. This first grid derived from the digital elevation model grid (DEM) is the flow direction map followed by flow accumulation, stream and catchment maps. The next steps in this research are to incorporate rainfall time series data from about forty stations to build a hydrologic data model within a GIS environment and to combine ArcGIS®/ArcHydro and HEC-HMS model, in order to produce a spatial-temporal model for floodplain analysis at a regional scale.

Keywords: Geographic Information Systems (GIS); Hydrologic Models; Flood Inundation Model; Paraiba do Sul River Basin

Resumen

Las inundaciones han aumentado dramáticamente en diferentes regiones de Brasil generando consecuencias para millones de personas y causando un enorme daño económico. Los mapas de riesgo de inundación son importantes para integrar datos geoespaciales y temporales en un mismo entorno computacional, permitiendo de este modo decidir, modelar y evaluar los riesgos. Este artículo analiza los diferentes niveles de integración entre SIG y modelos hidrológicos. Se presenta un estudio de caso en el cual todas las tareas para crear un modelo de entrada, edición de datos y visualización de resultados de salida estén disponibles dentro de un SIG. El área de estudio corresponde a la parte superior de la cuenca de Paraíba del Sur (porción del Estado de San Pablo), que comprende aproximadamente 15.300 km2 y está ubicada en el sudeste de Brasil. La cuenca del Río Paraíba del Sur tiene una gran importancia en la historia, cultura y economía del Brasil. A lo largo del río principal tienen lugar un gran número de actividades urbanas e industriales. Esta región cuenta con una base de datos adecuada para la dimensión de la cuenca que incluye mapas topográficos georeferenciados. Se utilizó el software ArcGIS®/ArcHydro, que tiene una red geométrica llamada HydroNetwork creada que fuera a su vez creada para producir varios mapas con formato "raster". Este primer cuadro derivado del cuadro modelo de elevación digital (DEM) se corresponde con el mapa de la dirección del flujo seguido por mapas de acumulación, drenaje y sub-cuencas. Los próximos pasos en esta investigación serán incorporar datos de series temporales de lluvias de unas cuarenta estaciones para construir un modelo de datos hidrológicos e integrar el software ArcHydro con el modelo lluvia-escurrimiento HEC-HMS para producir un modelo espacial y temporal para el análisis de inundaciones de llanuras a escala regional.

Palabras clave: Información geográfica, Sistemas (GIS); Modelos hidrológicos; Modelo de Inundacionesl; Cuenca acuífera de Paraiba do Sul

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1. INTRODUCTION

Studies in different parts of the world suggest that the number of disastersassociated with extreme weather and climate, such as floods, has increased through the 20thcentury (Changnon et al., 2000; Ashmore and Church, 2001;Guha-Sapir et al., 2004; Lugeri et al., 2010). Thistrend likely reflects different factors, such as a shift in the precipitation pattern, and the fact of a growing amountof the population living inflood-proneareasisincreasing. Residents that lived in low land or close to river banks are often highly vulnerable to flood hazard, especially when it happens in urban areas. For all these reasons, floodwater management and analysis became a growing topic of discussion among the government, communities and researchers worldwide.

In different regions of Brazil, floods have increased dramatically, affecting millions of people and inflicting huge economicaldamage. The situation is particularly dramatic in Southeast region, involving the states of São Paulo, Minas Gerais and Rio de Janeiro, which are responsible for more than 50% of the GDP in Brazil. Inundation has been recurrent in Sao Paulo, Rio de Janeiro, Belo Horizonte and other important cities. In January 2011, Brazil had its worst and deadliest natural disaster since 1900, where a heavy rain causedthe floods and the mudslides in mountain towns situated in thenorth of the city of Rio Janeiro.

Despite this situation, there are no national (and regional) projects by promoting flood hazard mapping for flood-prone areas in the urban environment, which could provide general knowledge of the flood hazard and could establish a measure for themanagement and prediction of these risk areas. National flood hazard maps have been created in different countries,such as the “Flood Harzard Mapping for Urban Areas (FHMUA)” for Malaysia(Toriman et al., 2009) and the “Digital Flood Insurance Rate Maps (DFIRMs)” elaborated by FEMA (Federal Emergency Management Agency), for the USA(National Research Council, 2007).

Producing flood hazard maps is important to integrate geospatial and temporal data in a same computational environment that allows risk assessment, modeling and decision support. The scope and scale of flood problems makes the Geographical Information System (GIS) software a powerful tool for its integrated management process. GIS is ideally suited for various floodplain management activities, such as base mapping, topographic mapping, and post-disaster verification of mapped floodplain extents and depths.

In this way, this paper aims describinga GIS applicationfor flood management and it presents a case study for the Paraíba do Sul basin situated in the Southeastern Brazil. This basin is one of most important in the country linking the major cities of the São Paulo and Rio de Janeiro..

2. A FOCUS ON GIS MODELING

Since the mid-1970´s, specialized computer systems have been developed to process geographical information in various ways, searching to connect digital maps and alphanumeric data that describe the features on the maps. The new generation of theGIS can store and analyze the topology of the data, i.e. the understanding of the context of spatial and attribute data(Delaney andNiel, 2007). Each spatial feature in a GIS has a unique geographic location, specified by its coordinates, and a unique identifying number by which it is connected to descriptive data in a relational database. GIS generally uses a Structured Querry Language (SQL), which is standard computer language designed specifically for accessing, querying and manipulating geodatabases in a powerful database management system.

As mentioned by Bernhardsen (2002),the GIS technology signifies much more than a software system that processes, stores, and analyzes geographical data; nowadays, the GIS development is allied to the power of the computer, opening an enormous range of possibilities for modeling and accurate decision.

Figure 1 shows different GIS domains and the importance of archiving, manipulation and a data-intensive analysis of the GIS (management components), as well as the modeling, the decision and the process-intensive GIS control (scientific component). However, process-intensive and data-intensive domains are no contradictory ones,and should be shared and integrated to the hydrology and the water resources (KovarandNachtnebel, 1993). Therefore, for those that studywater resources, it is necessary to find a balance between the process-intensive (modeling) and thedata-intensive (archival; management)

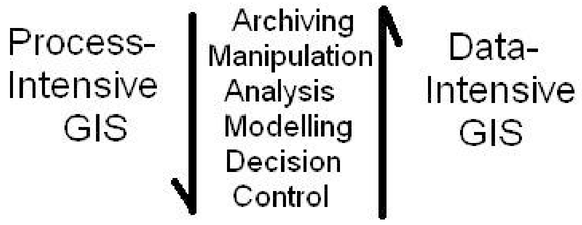


Figure 1 – A concept of GIS domains (Clark, 2000).

Within the large broad domain of water resources sciences, the priorities of GIS will depend upon context,in which modeling occupies a key position (Clark, 2000). This is because hydrology, catchment and fluvial systems interact closely in time and space. On the other hand, hydrological models simulate the flow of water, sediment, nutrients, whose physical diversity and complexity of the landscape should be considered and, consequently, tend to strength the spatial dimension.

Although the elements of hydrological modeling predate GIS by more than a century (Maidment, 1993), GIS and modeling have converted strongly over the last 20 years. Clark (2000) highlights that almost 60% of the whole papers in the 1993 and 1996 HydroGIS conference proceedings include the terms modeling, simulation or forecasting.Because the uncertainty of water resources management under climate change tends to increase, modeling and simulation are valuable tools for building alternative future scenarios.

However, geographic reality is continuous and infinitely complex when comparing with computer, which are relatively simple and can only deal with digital data. Therefore, difficult choices have to be made about how things are modeled in a GIS and how are they represented.

For understanding the modeling process related to a GIS (or *GIS data model*),we can think about different levels of data model abstraction (Figure 2). First, the *reality,*represents the real-world phenomena (buildings, streets, rivers, forests) and includes all the aspects that may or not be perceived by individuals. Second, the *conceptual model*, represents selected objects and processes that are considered relevant for a specific proposal. Third, the *logical model* is an implementation-oriented representation of thereality that is often represented as a diagram or lists. Lastly, the *physical model* (or computational model) corresponds to animplementation in a GIS, and often comprises tables stored as files or databases (Longley et al., 2008). Note that the expression *physical model* applied above is different of considering the expression *hydrologic physical model*, whose hydrological system is represented for formal mathematics terms. Physically–based models are the most suitable when studying internal catchment scenarios (Olsson and-Pilesjo, 2002).

The central role of the GIS in the modeling process may vary in different grades and stages. The set of possible relationships depends on the different application of the linkage as suggestsMaidment(1993) and showed bellow.

- Hydrological assessment to represent hazard or vulnerability (using arithmetic operators and weights for evaluating influences of significant factors);
- Hydrological parameters determination, whereby the GIS provides inputs to the model in terms of parameters, such as surface slope, channel length, land use and soil characteristics
- Hydrological modeling within the GIS,where temporal data are involved;
- Linking the GIS and hydrological models to utilize the GIS as an input and display device including real-time process monitoring.

Therefore, the relationship between GIS and modeling assumes different levels of integration and this issue will be discussed further.

3. DATA COLLECTION

A major problem that hydrologist and environmental professionals will treat during the next several years is *information overload* that means the inability to

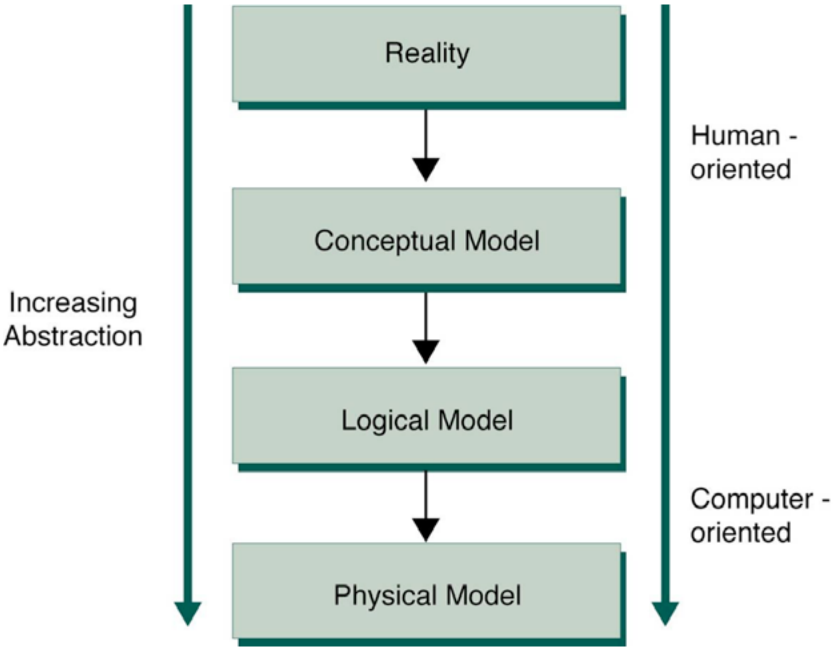


Figure 2 – Levels of abstraction relevant to GIS data model (Longley et al., 2008)

deal with available information using present methods (Dodson, 1993). In the early days of GIS, when geographic data were scarce, data collection was the main project task. Even today, data collection still remains a time-consuming, tedious and expensive process. Obviously, effectively using large sets will require a more integrated approach involving a series of sequential stages, as those displayed in figure3. Sequential stages could be used at different types of project,regardless of its level of complexity. A workflow commences with planning, followed by preparation, digitizing/transfer, editing and improvement and finally evaluation (Longley et al., 2008).

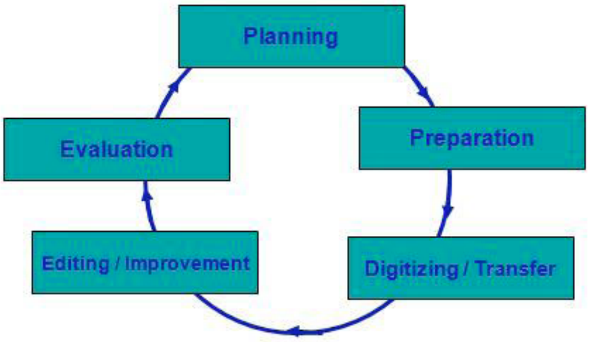


Figure 3 – Sequential stages of planning (Longley et al. 2008)

GIS can contain a wide variety of geographic data types originated from many diverse sources. From the perspective of creating geographic databases, it is convenient to classify geographic data as raster and vector and as primary and secondary, as well. (Table 1).

Table 1 – Different types of data (Longley et al., 2008, modified)

	Raster	Vector
Primary	Digital remote sensing images	GPS measurements
	Digital aerial photographs	Survey measurements
Secondary	Scanned maps	Topographic surveys
	DEMs from maps	Toponymy data sets

Primary data sources are those collected in digital format for using in a GIS project. Typical examples of primary GIS sources include raster satellite image such as Landsat, Aster® and Ikonos®images,and vector survey measurements which are captured using,for instance, highly accurate total station. Typical secondary sources include raster scanned coloraerial photographs or analog maps covering, for example, an urban area or a watershed of different sizes.

A major limitation to the application of GIS to hydrologic parameters computation is the lack of sufficient data on important characteristics such as land uses and soil. The LUCC (Land Use and Cover Change), a current joint project of IHDP (International Human Dimension of Global Environmental Change Program) and IGBP (International Geosphere-Biosphere Program) has a set of digital files covering different regions of the world. NATSGO is an example of soil database designed for regional and national planning for the USA. Similar soil database have been developed only in a few countries such as Canada, France and Netherlands (Nizeyimanaet al., 2002). Therefore, unfortunately, there are no consistent national or regional set of soil maps available in digital form in many parts of the world. This way, important hydrologic parameter, such as infiltration,is difficult to obtain because soil maps are not available atthe suitable scale.

The analysis of floodplains includes a large volume and variety of both primary and secondary sources data, which could be divided into geospatial and hydrologic data. This data can be obtained from different sources. Some of the main geospatial data used in floodplain management are discussed below.

3.1. Topographic Data

Much has changed since the early topographic maps madeby hand or “old” procedures based on paper map (analog cartography). Advances in survey techniques, instrumentation, and printing technologies, as well as the use of remote sensing products, have dramatically improved mapping coverage, accuracy, and efficiency. The information age has introduced a new cartographic product that is changing the face of mapping: digital data for computerized mapping and analysis. As mentioned by Robinson et al. (1995), the computer revolution in cartography preserves the basic elements of science but it provides two new functions: the *digital database*, replacing the printed map, and the *cartographic visualization* on many different media.

However, in spite of these amazing technological advances,in many countries large scale and accurate digital maps are not available for extent regions. Developed countries usually have 1:25,000-scale topographic digital maps - or even more accurate - covering large contiguous areas. In contrast, in many countries, typical mapping scales are at regional level (between 1:100,000 and 1:1,000,000). At this level, the areas to be investigated are large, covering several thousands of square kilometers, and the use of GIS for flooding management could be useful in the early phases of regional projects or in large engineering projects (Westen, 2002).

At local level (or municipality level), typical mapping scales are between 1:5,000 and 1:25,000 and the hazard maps may present a high quality accurate information. At this scale level – or higher –GIS software with 3D visualization tools could be of great use.

The absence in many countries of a higher-level cartography program supported by large governmental subsides clearly change the order of magnitude cost analysis of the projects, especially the smaller ones (see item 3.4).

3.2. Digital Elevation Model

The inclusion of topographic features, using digital elevation models (DEM) structures allows more physically realistic models. The global model GTOPO30 reflects a significant improvement in the quality and resolution of DEMs (Reed et al., 2002). GTOPO30 or local digital topographic survey can be used for computing floodplain elevations and mapping floodplain boundaries. TIN (Triangulated Irregular Network)data structure has the ability to precisely represent linear (banks, channel bottom, ridges) and point features (hills and sinks), which are critical to accurately define the channel and the floodplain geometry. Moreover, TIN associated with raster data (remote sensing) or vector data (topographic maps) provides an increase in the flexibility of modelingof surfacefrom raster modeling (DeMers, 2002) using, for example,theSpatial Analyst/Arc GIS®, the GRASS, the IDRISI®and the ERDAS®softwares.

3.3. Remote Sensing

In the last decades, satellite data have been successfully used in most phases of the flood disaster management (CEOS/IGOS, 1999). Earth observations satellites can be used in many phases of disaster prevention, by mapping geomorphologic elements, historical events and sequential inundation phases, including duration, depth of inundation, and direction of currents (Western, 2002). Floodplains have been delineated by using remotely sensed data to infer their extent from different criteria such as, topographic, pedologic, and botanical features(Dunne and Leopold, 1978). For the prediction of floods, low resolution NOAAAVHRR images, combined with radar data are used to estimate intensity and amount of precipitation, and coverage, and to determine ground effects such as the surface of soil moisture. Medium resolution Landsat and SPOT satellites have been used for producing flood-prone maps at scales varying between 1:30,000 and 1:100,000. High resolution IKONOS® and Quickbird® satellite images can be reasonably expected to produce more accurate delineation of flood prone areas, although the cost of data can also be prohibitive for a single project or organization. At the local scale, a large number of hydrological and hydraulic factors can be integrated with spatial resolution imagery using GIS, especially the generation of detailed topographic information using high precision digital elevation models derived from aerial photography, SPOT® or LiDAR® (Light detection And Range). An important feature of satellite and aerial photography systems is that they can provide stereo imagery from overlapping pairs of images. These maps are used to create a 3-D model from which contours and elevation maps can be created. Therefore, these data can be used in two or three dimensional finite element models for the prediction of floods in river channels and floodplains.

3.4. GIS data sources

As previously discussed, there are many sources and types of geographic data used for water resource projects in general and floodplain management more specifically. However, GIS data comes in many different forms and levels of accuracy and a large variety of prices. In spite of a decrease of the GIS data cost in the latest years, it can represent more than 40% of the total project, especially the smaller one. Therefore, developing your own datasets allows you to have total control over the content and accuracy but it can involve a substantial portion of cost of a GIS project.

In order to reduce the cost, Internet is the best alternative to obtain GIS data. The data include specialist geographic data catalogs as well as the sites of specific geographic data. There are many organizations that maintain comprehensive environmental database such as, Environmental System Research Institute (ESRI), Center for Information Earth Science Information Network (CIESIN), and Canadian Geospatial Data Infrastructure (CGDI). Table 2 shows some of the main organizations where useful data for floodplain management could be found. Elevation data can be obtained from different sources and a large variety of spatial resolution. Hydrologic database includes precipitation records, stream flow, and gauge records. Climatologic and hydrologic data set is represented by time-series data, which represent sequences of real-world observations or calculation. The hydro database of the Brazilian National Water Agency (ANA, in Portuguese) is an example of a comprehensive national hydrological database, which includes more than 2,000 streamflow stations associated with Brazilian streams. This database includes rainfall, evaporation, water quality and sediment data.

Table 2 – Type of data and source used to floodplain management

Type	Source[1]	Details
Elevation	NGA, USGS, SPOT image, NASA, INPE	DEMs, contours at local, regional, and global levels
Hydrology	Government agencies and national hydrological databases available for many countries (e.g. NHD/USGS, USA, ANA, Brazil)	including spatial rainfall and streamflow gage data
Soil type data	Government agencies (e.g. STATSGO/USA)	Very limited for many regions often depending on local surveys
Land use / land cover	LUCC, AVHRR/NOAA	High level of detail depends on large-scale aerial photography and commercial satellite remote-sensing
Flood zones	Many national and regional government agencies, e.g. FEMA/USA	National Hydrological databases are available for many countries

[1] NGA – National Geospatial-Intelligence Agency, USGS – United State Geological Survey, INPE – Brazilian Agency for Space Research, NHD – The National Hydrography Database, STATSGO – Soil Survey Geographic Data, United State Department of Agriculture, AVHRR/NOAA – Advanced very High Resolution Radiometer/National Oceanic and Atmospheric Organisation, FEMA – Federal Emergency Management Agency/USA.

4. GIS AND FLOODPLAIN MODEL DATA

GIS is ideally suited for floodplain management and prevision for its capacity of linking and integrating geospatial and temporal data.Moreover, the integration of the GIS with floodplain computer models allows users to devote more time to understanding flooding problems and less time to the mechanical tasks of preparing input data and interpreting output.

The primary challenge lies as the difficulty in integrating GIS and hydrological data models in a combined program.Shamsi (2002) defines a useful taxonomy to define the different ways that a GIS can be linked to computer models and how simulation or prediction will be handled bya non-GIS hydrological model that is coupled to the GIS data input or output data. The three methods of GIS linkage suggested by Shamsi (2002) are:

a. Interchange method - This method employs a batch processing approach to interchange a GIS and a computer model. Both the GIS and the model are run separately and independently. This is the easiest method and the mostly used nowadays.The GIS software is used to extract the floodplain cross-section from the DEM data, runoff curve numbers from land use or soil layers are some examples of the interchange methods.

b. Interface Methods - The model is executed independently from the GIS; however, the input file is created, at least partially, from within the GIS. The main difference between the interchange and interface methods is the automatic creation of a model input file.The HEC-HMS(Hydrologic Modeling System – Hydrologic Modelling System) model developed by U.S. Army Corps of Engineering associated with GIS packagesis a good example of theinterface method.HEC-HMShas a graphical user interface that allows the users to edit, execute and view model data in a windows environment.

c. Integration method –It is a combination of a model and a GIS in a way that the combined program offers both the GIS and the modeling functions. This method represents the closest relationship between the GIS and the floodplain models. Two integration approaches are possible: 1) *GIS Model Integration*-all the four tasks of creating model input, editing data, running the model, and displaying output results are available in GIS. 2) *Model Based Integration* -GIS modules are developed in or are called from a computer model.

5. FLOODPLAIN MAPPING SOFTWARE

There are several well-known floodplains mapping software currently in use elsewhere. Each individual component process of these models can vary significantly because they could serve for a different purpose. Some floodplain mapping and modeling software examples are presented below.

MIKE FLOOD® is a complete toolbox for flood modeling,including a wide selection of 1D and 2D flood simulation engines, enabling to virtually model flood problem, whether it involves rivers and floodplains in different environments. Typical MIKE FLOOD® applications include rapid flood assessment andflood hazard mapping. MIKE FLOOD® also has GIS linkage capabilities, which can be used to produce inundation maps as a result of levee or embankment failures. *HEC-GeoRAS* system is afree software composed of a set of procedures, tools, and utilities for processing geospatial data in ArcGIS®, which intends to calculate water surface profiles in a full network of channels, a dendritic system or a single river reach. Water surface profile data and velocity data exported from hydraulic modeling such as HEC-RASmay be processed by HEC-GeoRAS for GIS analysis (see next topics) for floodplain mapping, flood damage computations, ecosystem restoration, and flood warning response (see next topic). *RiverCAD®*is a river modeling software that supports HEC-RAS and HEC-2 within AutoCAD®. RiverCAD® computes water surface profiles for modeling bridges, culverts, levees, floodway delineation, stream diversions and so on. RiverCADallows the creation of 3D CAD drawings of HEC-RAS showing the extent of water surface regarding the ground topography. *ArcGIS Hydro Data Model* -is an ArcGIS®geodatabase model, which provides a standardized framework, into which, the data forms an integrated water resources modeling and mapping database. Because it will be presented a case study using ArcGIS®ArcHydro Data Model, this software will be discussed in more details below.

6. THE ARCHYDRO DATA MODEL

ArcHydro is a geospatial and temporal data model for water resources that operate within ArcGIS®. ArcHydro has an associated set of tools, built jointly by ESRI (Environmental System Research Institute) and CRWR (Center for Research in Water Resources), which interconnect features and different data layers, and support hydrologic analysis (Maidment, 2002). ArcHydro is a data structure that support hydrographic simulation models, but it is not itself a simulation model. ArcHydro focuses on the description of surface water hydrology, despite the fact that there is a separate data model called ArcHydro Groundwater Data Model that should enable the integration of surface and groundwater information.

The design of the ArcHydro is a hydrologic information system, which is a synthesis of geospatial and temporal data supporting hydrologic analysis. Therefore, ArcHydro provides a systematic way to link time series data on water management to geospatial data on the location. ArcHydro can even be applied at the scale of a small urban subdivision to study runoff pattern through buildings and storm sewers (Maidment, 2002).The ArcHydro, also, allows hydrological models to be linked with GIS through a common data storage system. For a long time, hydrologists have wanted to apply GIS data using spreadsheet (MerwadeandMaidment, 2002). In this way, ArcHydro facilitates the integration with hydrologic modeling, since the ArcHydropersonalgeodatabase is a Microsoft Access and Microsoft Excel and Microsoft Access are interchangeable (Figure 4).

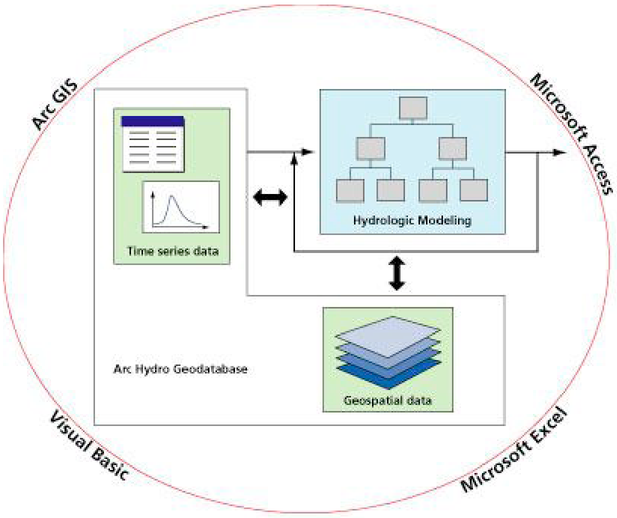


Figure 4– Interfaces for hydrologic modeling (Merwade&Maidment, 2002)

HEC-HMS is considered a standard model for the design of drainage systems making it possible, for example, to quantify the effects of land use change on flooding (Singh andFrevert, 2006).A hydrologic model suchas HEC-HMS transforms storm rainfall input to streamflow discharge output usingwatershed characteristics, such as drainage area, slope,land cover and soil type. Many of these types of data can be estimated from a GIS database. The runoff information from the hydrologic model can then be combined with stream cross-section information model such as HEC-RAS, to determine flooding parameters. An interesting example of GIS and HEC-RAS integration was presented by Kraus (2000) for a small watershed situated in Texas, USA. The floodplain data developed in ArcView (a former version of ArcGIS) was imported into the HEC-RAS, where it was combined with field data in order to construct a full floodplain cross section.

HEC-HMS and HEC-RAS are written in object-oriented programming languages and, during the 1990s, special purpose GIS interface was constructed to supply geospatial data such as HEC-GeoHMS/HEC-GeoRAS systems.HEC-GeoRASallows a professional with little GIS training to use the ArcGIS to develop geometric data for import in the HEC-RAS and view water surface profile data (Ackerman, et al., 2000).

An interesting application involving an integration of ArcHydro database and HEC-GeoHMS tools was developed by Kawasaki et al. (2008) for analyzing the effects of precipitation change and land use change in the LowerMekongRiver. Spatial and temporal data were used to create 2025 and 2050 scenarios considering the potential impacts of climate change and socio-economic development.

7. CASE STUDY

7.1. Study area characteristics

Different types of flooding (river floods, flash floods, coastal floods) have different characteristics with respect to the areal extent. Topographic maps and remote sensing images can be used for mapping geomorphologic elements of the landforms and the fluvial system supports wherever possible by information on past flood and high-scale topographic maps, where terraces and levees can be recognized (Westen, 2002). However, detailed geomorphological features are not available for large hydrographic basins worldwide.

One of the main problems of integrating GIS and hydrologic modeling regarding floodplain management and flood mapping is that a large data collection is necessary including rainfall-runoff and hydrograph analysis and gauge measurements. Rainfall and streamflow time series data need to have, at least, 20-30 years of historical data. Then, several efforts have been developed looking for more simple methods for delineating flood hazard zones. An interesting example was given by Suryanta et al. (2010), for delineating map flood hazard. These authors used indicators such as geomorphological, land use and isohyets maps and a record of inundation.Dewan et al. (2007), show a simple and cost effective way to use GIS and remote sensing, for creating flooding hazard map from a available dataset including land use, elevation and geomorphic units.

Therefore, this paper presentsa case study, where a limited amount of spatial and temporal data is available. The study area corresponds tothe upper section of the Paraíbado Sulbasin (Sao Paulo State portion), comprising nearly 15,300 km^2 and situated in the Southeast of Brazil (Figure 5).

Paraiba do Sul basin has a large importance in the history, culture and economy of Southeast Brazil with high urbanization and industrial activities along a part of the main river. The basin is characterized by heterogeneous geomorphology, hydrology and soils with elevations varying from about 400 min extentalluvial plains up to more than 2400 m in the Mantiqueira and Serra do Mar mountain ridge. Historically, human activity imposed dramatic transformations of the regional landscape with a reduction in forested areas from nearly 81% to 8.0% over the last 300 years (Fujieda et al., 1997). Currently, the landscape is a complex mosaic of grazing, forest, and urban areas. The population in the Paraíba valley increased 300 per cent in the last thirty years, from approximately 518,000 in 1960 to approximately 1,690,000 in 2000. Cities continue to expand near, or on alluvial plains contributing to the reduction and elimination of wetland ecosystems and occupying a significant part of the floodplain.

Because of its strategic geographical position, multipurpose reservoirs (electricity generation, flood control and flow regulation) were built first in the 1950s, and later in the 1970s. Since 1952, water is diverted from the Paraíba do SulRiver into the GuanduRiver water treatment planin the Rio de Janeiro state.

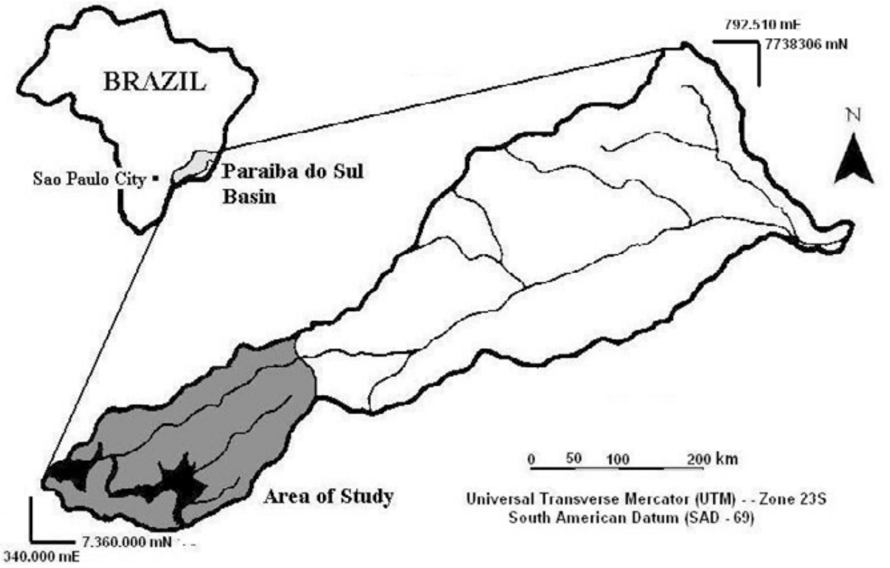


Figure 5 – Study area (Paraiba doSul basin – São Paulo State)

About 8.7 million people living outside of the basin (in Rio de Janeiro Metropolitan Region) depend on its resources for water supply. In the study area, mean river discharge is 217m^3/s; the largest withdrawals of water are made for agricultural irrigation 10.4 m^3/s, followed by industrial use, 6.5 m^3/s and domestic use, 3.4 m^3/s (Sao Paulo State Government, 2002). Therefore, the Paraiba do Sul River is an example of a complex multipurpose water resources management that links hydropower production to agricultural, industrial and domestic water use.

Previous studies have documented the bimodal character of the annual cycle of precipitation in southeast Brazil(Braga andMolion, 1999), with dry and wet seasons consistent with the transition from tropical to mid-latitude climate regimes.In the Paraíbado Sul basin, the average annual precipitation is in the order of 1,400 mm, but exhibits large interannual variability ranging between 800 mm and 2000 mm. Severe droughts occurred in 1943/1944, 1953-1957, 1963, 1968, 1984, 1994, 1997 and 2001; whereas 1947, 1976, 1983 and 2000, 2008-2010 were exceptionally wet years. Dry and wet spells (1 - 2 years) alternate ubiquitously in the observations. Therefore, the region presents a high uncertainty in the long-term assessment of water resources.

In 2001, a severe drought was blamed by the severe reduction in water levels in the reservoirs of many Brazilian hydroelectric power plants (Simoesand Barros, 2007). By September, 2001, the reservoirs were working at minimum capacity (about 20% of the total volume), evidence of the failure of existing energy and water resources management plans to meet unexpected shortages. The shortage period remained until 2004 (Figure 6); by 2007, a wet period starts, which remains until today (January/2011). Reservoirs were now almost full and several flood events have occurred in the latest years affecting thousands of people. In 2010, São Luis do Paraitinga, a small town located about 200 km from São Paulo, was devastated by a flood, where many historical buildingswere collapsed. In the last three years, other towns of different sizes have been affected along the Paraiba do Sul River.

Then, this case study intends to present the first phases of a project, which intends to understand the hydrological response of a large river, as Paraiba do Sul, to the extreme events and its impacts for an extent floodplain. Therefore, this research intends to explore the possibilities of synthesis of geospatial and temporal hydrologic database. In this first stage, we use the ArcHydro framework, which is a simplified version of the ArcHydro storing informationabout river network, watersheds, and monitoring points.

7.2. Database

Several topographic and thematic maps and database are available in the study area (ArcGIS® and AutoCAD® formats). Digital topographic maps include surveys undertaken at 1:250,000 and 1:50,000 scales covering the total basin. For the basin size (13,5000 km), this level of topographic scale is suitable and represents a better situation that those found in other Brazilian regions. Digitalized topographic maps at a larger scale (1:10,000) are available for only a very small fraction in the basin. Thematic maps include geology, geomorphology, pedology, and land use/land cover. The Digital Elevation Model (DEM) was derived from a topographic map at

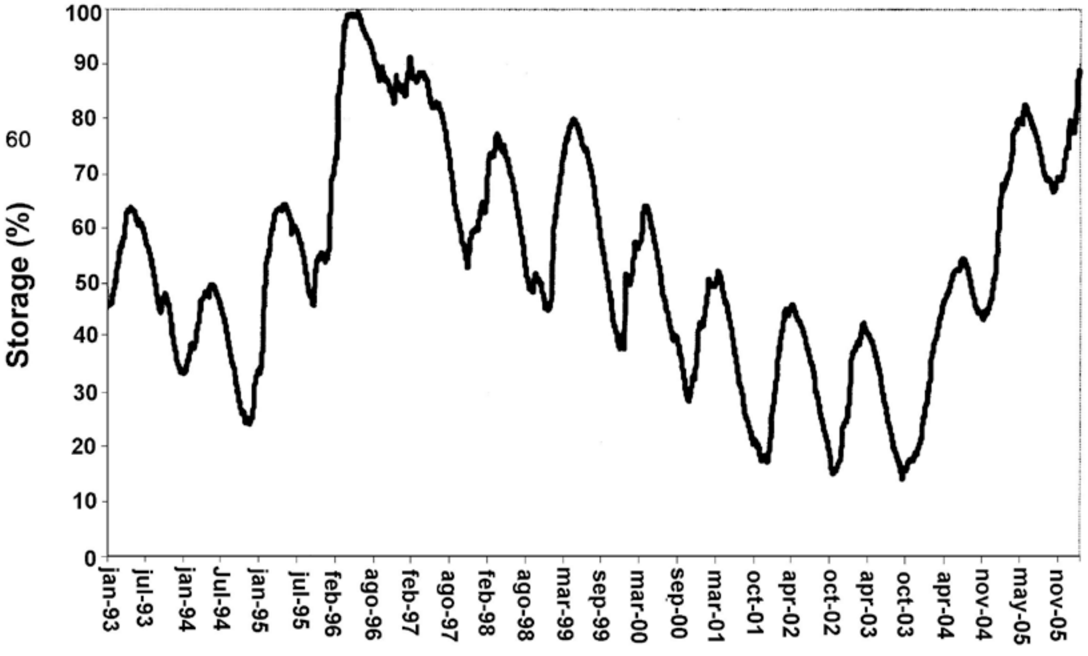


Figure 6 -Variation of water levels in Paraiba do Sul basin reservoirs expressed as percentage (%) of total reservoir water storage capacity between 1993 and 2005.

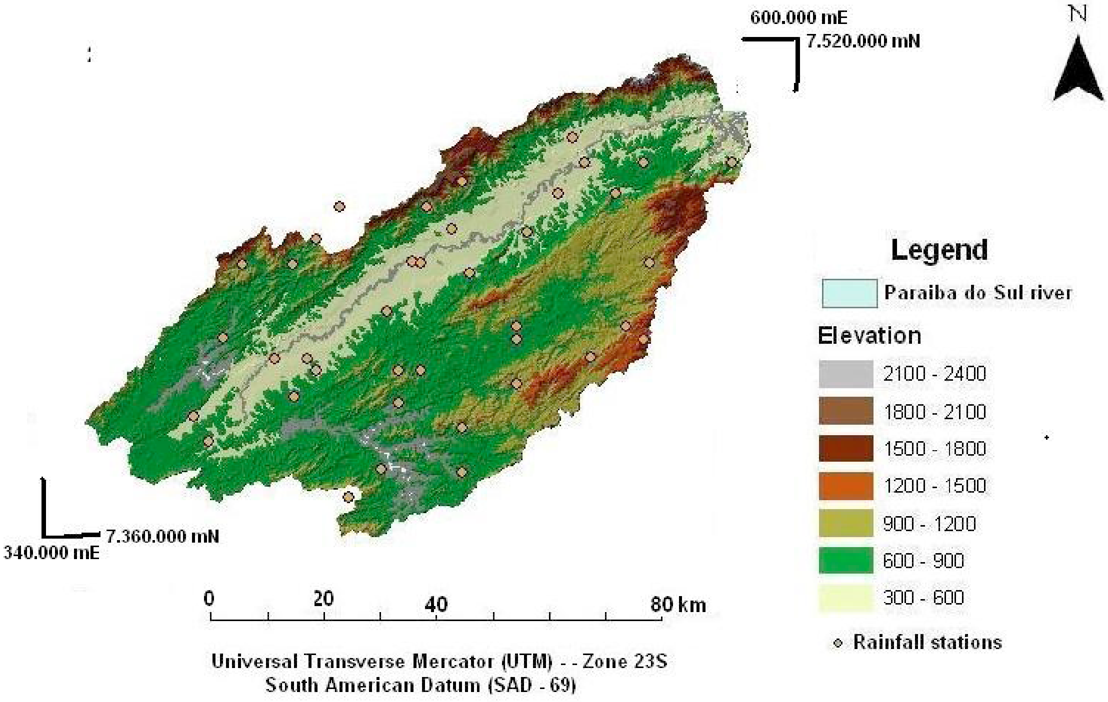


Figure7 – TIN model and select rainfall stations

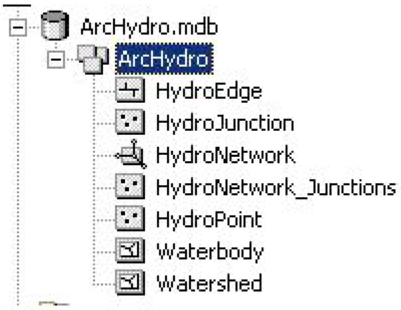
1:250,000 scale, 30-by-30 minute quadrangle IBGE maps. A hydrographic geodatabase including stream watershed has been compiled using the ArcGIS® 9.2 software and extensions (Spatial Analyst® and ArcHydro). The hydrological data include a network of 107 raingauges(Figure 7) installed at a variety of altitudes (450 m – 1700 m), some of which have beenin place since the 1930's, and streamflow gage data maintained by the DAEE (Water and Electric Energy Department, Sao Paulo State).

7.3. Results

Preparing the data

The first step in creating an Arc Hydro dataset is to collect GIS data, commonly represented as feature classes, which are collections of geometric objects (points, lines, or polygons) that share common themes and attribute types. A typical resource for hydrological data is the National Hydrography Dataset (NHD) for the United States. The NHD includes everything necessary for a simple Arc Hydro model. However, in many regions worldwide, a considerable preparation is needed before the database can be loaded into the ArcHydro database.

After preparing the data, a personal geodatabase is created, in which all of the Arc Hydro objects (feature classes, tables) will be stored. During this process, it is important to select a correct projection system and spatial reference frame, which should be one that will accurately represent different geographic areas of the watershed of interest.Geodatabeworks best when the feature classes have the correct class names.For that, aArc Hydro schema is applied, which mainly consists of objects such as feature datasets, feature classes and tables, and relationships among them (for more details, see Maidment, 2000).Figure 8 shows a typical geodatabasewhere *Hydropoint,* represents point features such as gauge station, *Hydroedge* represents line shapefile such as drainage, and *Watershed* represents a polygon feature class, which contains any subdivision of the landscape into drainage areas.



ArcHydro.mdb
ArcHydro
HydroEdge
HydroJunction
HydroNetwork
HydroNetwork_Junctions
HydroPoint
Waterbody
Watershed

Figure 8 - A geodatabase with typical Arc Hydro feature classes

One of the important characteristics of the ArcHydro principles is to construct water flow network.The final Arc Hydro Network creates a well-defined topology among polygon features (watershed boundary), lines (drainage system) and points (monitoring points). Therefore, HydroEdge and HydroJunction form a geometric network called HydroNetwork (Figure 8). This way, ArcGIS can now be used to trace paths between any two network locations.Figure 9 shows the

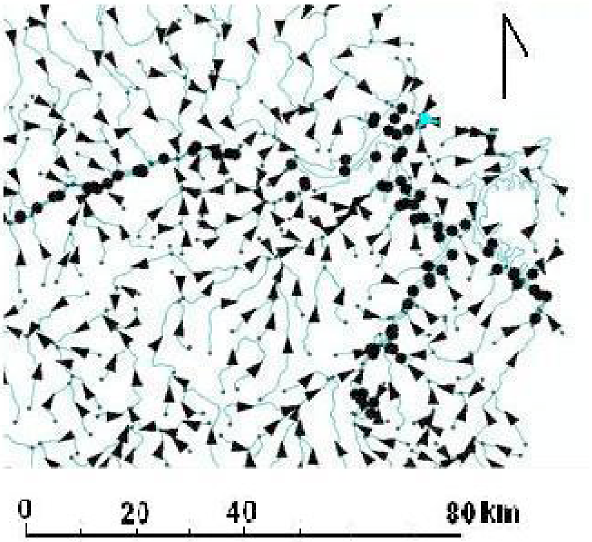


Figure 9 – Drainage network connectivity determined by theflow direction grid

topological connectivity of drainage network of the study area near the river outlet.

Implementing a drainage system

The first step in hydrological modeling is to define a model area by defining the outline of the watershed boundary. Since the model is distributed (e.g. is supposed to describe flow processes in each and every point inside a catchment) and more topographic information is needed,it is normally used a digital elevation model (DEM), for drainage delineation and for the estimation of topographically related parameters. DEM better represents the land surface and drainage flow, as compared to TIN, because of its regular cell structure. In this particular case of this study, this gridded data is derived from a TIN surface using ArcGIS®geoprocessing tools.

All ArcGIS® raster operation involved in the watershed delineation are derived from the premise that water flows downhill according the eight-direction pour point model (for more detail see, for instance, Oliveira et al., 2000).

This first important grid derived from the digital elevation model grid (DEM) is the flow direction grid (Figure 10a). A flow direction grid consists of values that indicate which neighboring cell the water will flow from. The cell values are the flow directions, which can only have eight possible directions for the water to flow (eight-direction pour point model). It is important to note that the DEM must have enough precision of elevation measurement to support correct flow direction determination. Large extents of flat areas might produce a natural drainage pattern. The Paraiba do Sul basin could be an example of such situation, where floodplain associated with the Paraiba do Sul River occupies an expressive area (Figure 10b).

Flow accumulation is calculated from the flow direction grid. As highlighted by Oliveira et al. (2000) from the physical point of view, flow accumulation grid is the drainage area measured in units of grid cells. Therefore, it indicates how many cells are upstream or upslope of the current cell. Flow accumulation has been used along with the flow direction, flow length and slope for flood forecasting (Chen et al., 2003). The flow accumulation grid for the Paraiba do Sul basin clearly shows how drainage areas are accumulatedin the downstream sector of the study area (Figure 11a). With a flow accumulation grid, streams may be defined through the use of a threshold drainage area or the flow accumulation value (Oliveira et al., 2000). The cell values are assigned as 1, where there is a stream and NODATA elsewhere. Therefore, all the stream cells are labeled identically with a value of 1, as showed in figure 11b.

To define catchments for each stream link, the flow direction grid is used to define the zone of cells whose drainage flows through each stream link (Oliveira et al., 2000). The results of the delineation are stored in a catchment grid. Figure 12 shows catchments and hydrographic reaches for the study area.Note each hydrographic reach hasonly one catchment. This raster grid may be converted into a set of catchment polygons using ArcHydro (or ArcGIS) raster-vector conversion functions. This is useful for finding out what geographic features are in the each catchment.

PARTIAL CONCLUSION

In recent years, the attention of hydrologist and watershed professionals has been turning to the problem of providing a spatial view of the hazard. Then, the potential for the use of GIS technologies in floodplain management and flood mapping are huge.

The methodology of mapping flood hazard is still being developed involving a large amount of techniques and approaches. On the other hand, it is a challenge to keep up floodplain mapsupdated due to the advance of the urbanization or others expressive land use change.

Particularly in developing countries, the use of prone-flood maps is still limited by lack of appropriate scale of data and GIS-hydrology experts. The demand for GIS-based analysis systems in flood plain analysis will increase in the future, as more detailed digital environmental sets become available. Meanwhile, an alternative could be the development of methodologies based on more simple approaches, which considers a limited number of inputssuch as rainfall, slope contours, geomorphologic features, and land use. Besides, the selected approach should facilitate the integration between spatial and temporal data. An example is the combination of the ArcGIS and the HEC-HMS to produce detailed terrain models and floodplain analysis. However, other GIS software and

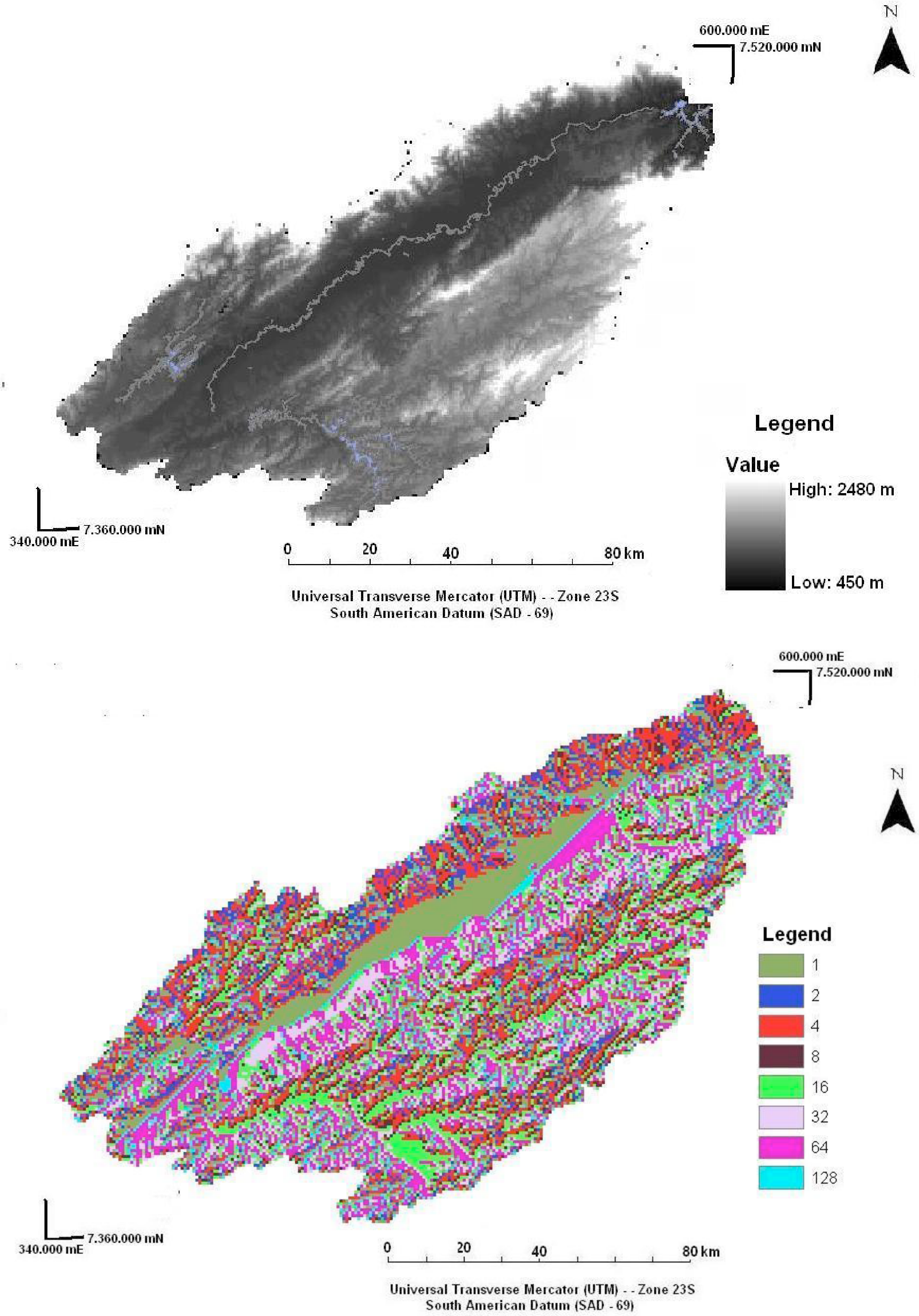


Figure 10 – (a) Digital elevation modelof the Paraiba do Sulbasin (São Paulo State portion); (b) The flow direction grid of the Paraiba do Sul basin

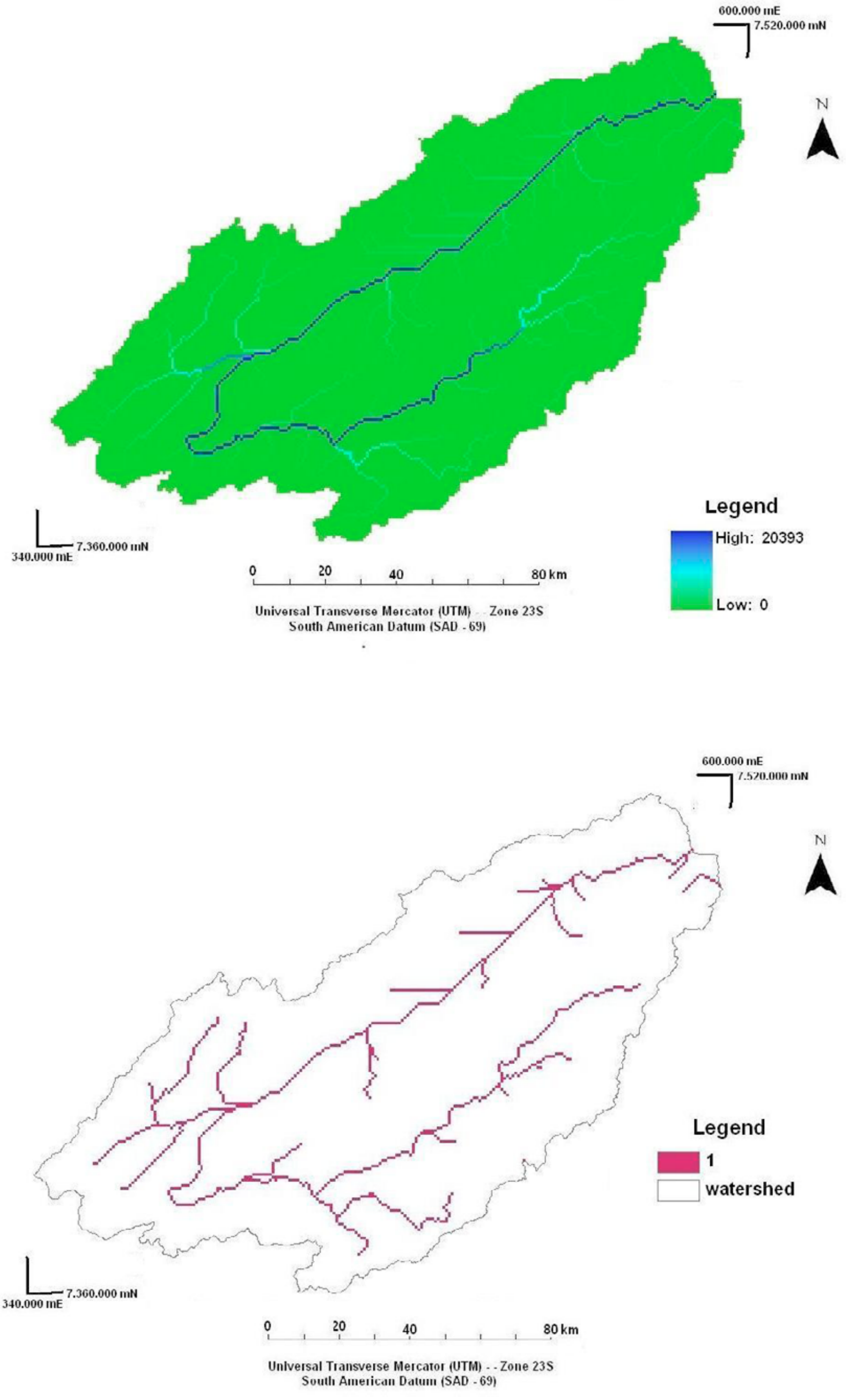


Figura11–(a) Flow accumulation grid of the Paraiba do Sul basin; (b) Streams definition

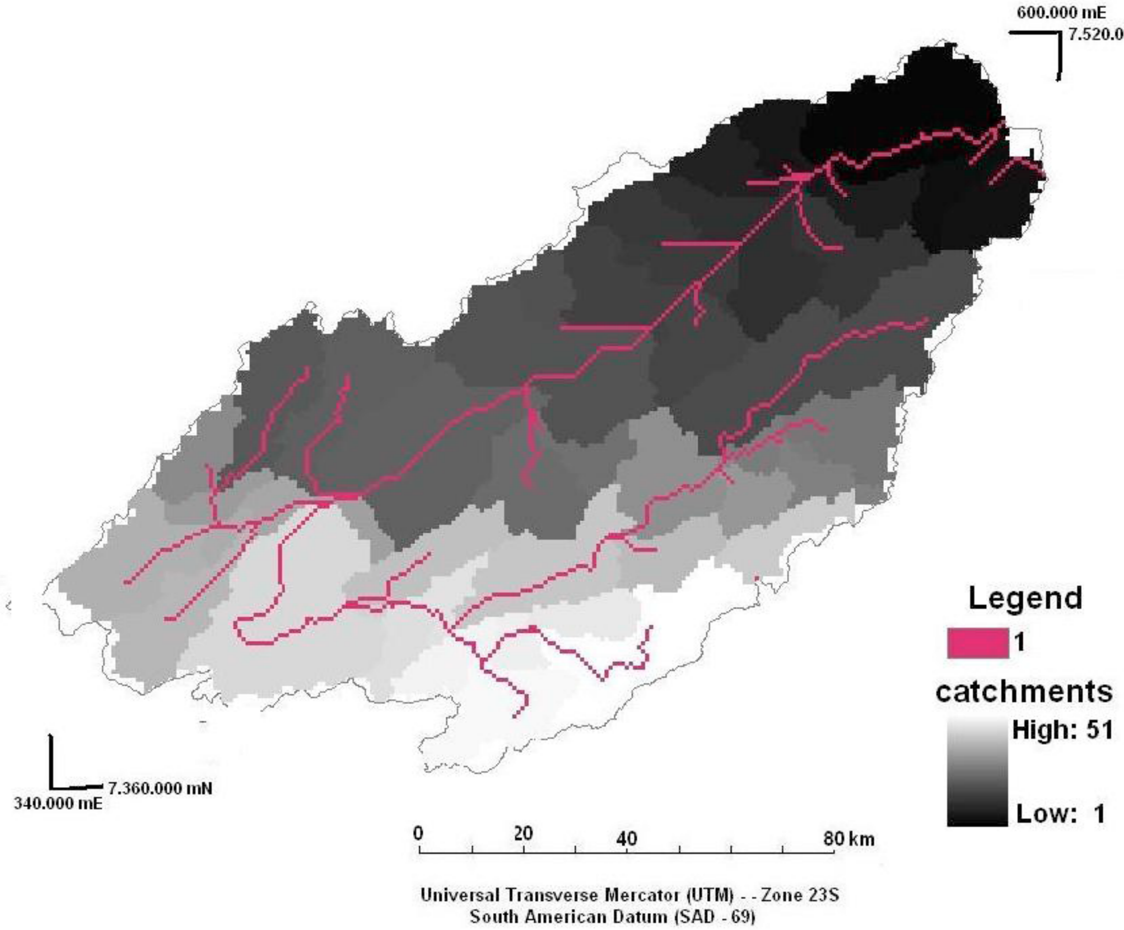


Figure12 – Catchments and drainage lines of the Paraiba do Sul basin

modeling software could be used for the same proposal.

The case study presented in this paper has a database which is suitable for the basin dimension including topographic maps at scales 1:250,000 and 1:50,000, and an expressive rainfall gauges network. Geological and land use maps are available at a regional scale (1:250,000) but an appropriated scale for soil data is not available.

The next stepsin this research are:a)to incorporaterainfalltime series data from forty-two stations in ArcHydro to build a hydrologic data modelwithin a GIS environment and b), to combine ArcGIS®/ArcHydro and HEC-HMS hydrologic model, in order to produce a spatial-temporal model for floodplain analysis at a regional scale.

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APPLICATION OF SCALE INVARIANCE PROPERTIES OF RAINFALL FOR ESTIMATING THE INTENSITY-DURATION-FREQUENCY RELATIONSHIPS AT UBERABA, IN SOUTH-CENTRAL BRAZIL

APLICACIÓN DE LAS PROPIEDADES DE INVARIANZA DE ESCALA DE LLUVIAS PARA LA ESTIMACIÓN DE LA RELACIÓN INTENSIDAD-DURACIÓN-FRECUENCIA EN UBERABA, EN EL CENTRO-SUR DE BRASIL

Mauro Naghettini*

Abstract

In this paper, the properties of scale invariance of rainfall, in time domain, are investigated and applied in order to estimate the intensity-duration-frequency (IDF) relationships for the town of Uberaba, located in the Brazilian State of Minas Gerais, where only records of daily rainfall depths are available. The assumption of simple scaling (scale) implies in direct relationships between the moments of different orders and the rainfall durations, which can be used to derive IDF relationships from larger durations. As short-duration rainfall records are not available at the Uberaba gauging station, the simple scale invariance properties are verified for sites with sub-daily records and then transferred to the location of interest. At all recording gauging sites investigated in here, the plots of moments of order q versus durations revealed an inflection point around the duration of 1 hour, which indicates a distinction between the prevalent types of precipitation according to their respective durations. This common behavior was kept in transferring the short-duration rainfall information to the location of Uberaba. The resulting IDF relationships were then compared to IDF estimates at locations nearby and the results are discussed. The paper's conclusions also discuss the attributes and limitations of the estimation method.

Keywords: Heavy rainfalls, Scale invariance, IDF relationships.

Resumen

En este artículo, se estudian y aplican las propiedades de invarianza de escala de lluvias en el dominio del tiempo, con el propósito de estimar la relación intensidad-duración-frecuencia (IDF) para la ciudad de Uberaba, ubicada en el Estado brasileño de Minas Gerais, donde únicamente se dispone de datos de densidad diaria de lluvia. La premisa de invarianza simple de escala involucra una vinculación directa entre los momentos de distintos órdenes y la duración de lluvia, lo cual puede ser empleado para deducir las relaciones IDF a partir de las duraciones más largas. Como los datos de densidad sub-diaria de lluvia no se hallan disponibles en la estación pluviométrica de Uberaba, las propriedades de invarianza simple de escala son previamente verificadas con datos sub-diarios obtenidos en sitios relativamente cercanos, y después transpuestas para el sitio de interés. En todas las estaciones con registros de alturas sub-diarias de lluvia aquí estudiadas, los gráficos de los momentos de orden q versus las duraciones, revelan un punto de inflexión alrededor de la duración de 1 hora, el cual sugiere un comportamiento distinto entre tipos prevalentes de precipitación en conformidad a sus respectivas duraciones. Este comportamiento común fue mantenido en la transferencia de la información de las lluvias de corta duración para la localidad de Uberaba. A continuación, las relaciones IDF así alcanzadas fueran confrontadas con estimaciones IDF de sitios cercanos y los resultados son aqui analizados. Finalmente, las conclusiones de este artículo presentan una discusión de los atributos y limitaciones del método de estimación propuesto.

Palabras clave: Lluvias intensas, Invarianza de escala, Relación IDF.

1 – INTRODUCTION

The intensity-duration-frequency (IDF) relationship of heavy rainfalls is certainly among the hydrologic tools most utilized by engineers to design storm sewers, culverts, retention/detention basins, and other structures of storm water management systems. An at-site IDF relationship is a statistical summary of rainfall events, estimated on the basis of records of intensities abstracted from rainfall depths of sub-daily durations, observed at a particular recording rainfall gauging station. At some particular site of interest, there might be one or more recording rainfall gauging stations operating for a time period sufficiently long to yield a reliable estimate of the at-site IDF relationship. In other locations, however, these recording stations may either not exist or have too few records to allow a reliable estimation of IDF relationships.

Because daily precipitation data are by far the most accessible and abundant source of rainfall information, it is appealing to develop methods to derive the IDF characteristics of short-duration events from daily rainfall statistics. The early attempts to derive short-duration rainfall intensities from daily data made use of empirical proportionality factors, which are supposed to be valid at a specific location or over a par-

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ticular geographic region (see for instance Bell, 1969; DAEE/CETESB, 1980). More recently, research has focused on the mathematical representation of rainfall fields both in time and space, including the development of scaling invariance models to derive short-duration rainfall intensity-frequency relations from daily data (see for example Burlando and Rosso, 1996; Menabde et al., 1999; De Michele et al., 2002).

Scaling invariance occurs when the connections among the statistical descriptors of a given phenomenon at different scales are constant and defined by a scale factor. The statistical descriptors can be scaled either by a single factor (simple scaling) or by a more complex function of the scale (multiscaling). As rainfall is concerned, scaling its statistical descriptors in time/space is related to the study of its fractal properties or, in other terms, the way in which rainfall organizes itself in self-affine cell clusters in time/space (Bara et al., 2009). For more theoretical details on scale invariance properties and rainfall IDF relationships, the reader is referred to Burlando and Rosso (1996) and Menabde et al. (1999).

This paper aims (i) to present a brief introduction of scale invariance as applied to rainfall events, (ii) in order to derive the IDF relationship from daily data for the town of Uberaba, located in south-central Brazil, and (iii) finally provide some discussions of the results and some concluding remarks. The paper is organized in six additional sections. The next section provides a description of the available data at Uberaba and outlines the sequential steps to be followed in this case study. Section 3 provides the necessary theoretical background on the simple scale invariance as applied to IDF estimations. The next two sections describe the application of simple scaling properties to estimating the IDF relationship from the daily rainfall data available at Uberaba. Analysis of the results and the main conclusions are provided in the last section.

2 – THE AVAILABLE DATA

The data available for the study described herein are the daily rainfall depths observed at the gauging station located in Uberaba, a town of 296,000 inhabitants located in the Brazilian state of Minas Gerais, in south-central Brazil, at coordinates 19°44’52’’ south and 47°55’55”, as illustrated in Figure 1. The rainfall gauging station is operated by the Brazilian National Institute of Meteorology (INMET) under the code 83577. The period of available data spans from 1914 to 2012, with 19 incomplete years containing one or more missing data during the rainy season (from October to March). Figure 2 depicts a chart of the 80 annual maximum daily rainfall depths, according to their chronology in calendar years. In order to preserve the essential statistical features of at-site maximum daily rainfall, missing data for incomplete years were not filled in by data available at nearby stations.

In addition to the annual maximum rainfall depths, depicted in Figure 2, two other sources of information were available for this study. The first one refers to the IDF equations available for two locations relatively close to Uberaba: the one estimated for Barretos, at coordinates 20°33’26’’ south and 48°34’04” west, and the other for the location of Catalão, at coordinates 18°09’57” south and 47°56’47” west. These locations are also indicated by arrows in Figure 1. The second source refers to the IDF equation estimated to the town of Uberaba by Freitas et al. (2001), through interpolation of regional data observed at some recording gauging stations within the entire state of Minas Gerais, the boundaries of which extend over a total surface area of 586,528 square kilometers.

As at-site sub-daily rainfall data were not available, estimation of the IDF relationship for Uberaba from the available records would have necessarily to rely on some strategy to disaggregate daily data into sub-daily quantities. Among the common strategies are (a) the use of empirical proportionality factors and (b)

Detail A: map of the case study area.
Arrows: main rainfall gauging stations.

Figure 1 – Location of Uberaba, in south-central Brazil. (http://maps.google.com.br)

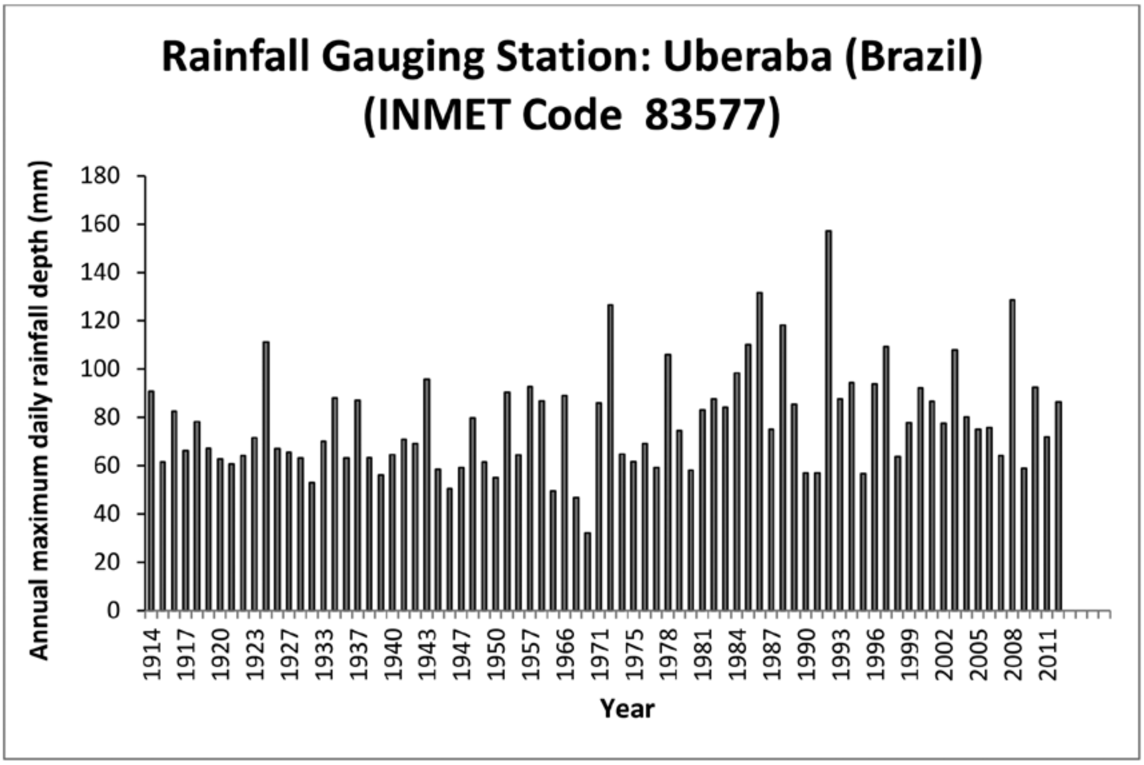

Figure 2 – Annual maximum daily rainfall depths, in millimeters per day, observed at the gauging station of Uberaba (INMET code 83577)

the use of scale invariance properties between daily and sub-daily intensities. In the present study, strategy (b) has been selected for the following reasons:

- In the last two decades, the study of scale invariance properties and their use to IDF estimation have been the focus of many theoretical and applied works, such as Gupta and Waymire (1990), Burlando and Rosso (1996), Menabde et al. (1999), Naghettini (2000), Gerold and Watkins (2005), Minh Nhat et al. (2008) and Bara et al. (2009), thus providing a consistent method for dealing with temporal statistical downscaling of hydrometeorological variables;
- Application of scale invariance properties to IDF estimation has been performed for a number of locations in the Brazilian state of Minas Gerais, providing good results with relatively simple implementation procedures (Naghettini, 2000);
- The so-called proportionality factors (DAEE/CETESB, 1980), calculated as empirical ratios between sub-daily and daily rainfall data averaged among a number of sites, are in fact generic quantities that do not account for the local features affecting rainfall at a given location and for the statistical dependence that may exist between these ratios and the return periods.

The next section presents the theoretical foundations of simple scale invariance, as employed in estimating IDF relationships of short duration point rainfall.

3 – THEORETICAL BACKGROUND

According to Koutsoyannis et al. (1998), for a given return period, IDF relationships are particular cases of the following general formula

$$i = \frac{w}{\left(d^{\nu} + \theta\right)^{\eta}} \tag{1}$$

where *i* denotes the rainfall intensity of duration *d*, and *w*, ν, θ, and η are non-negative coefficients. Koutsoyannis et al. (1998) also proposed a numerical exercise, in which they show that the errors resulting from imposing ν=1 in equation (1) are much smaller than the typical parameter and quantile estimation errors from limited size samples of rainfall data. Hence, considering $\nu \neq 1$ as a model over-parameterization, Koutsoyannis et al. (1998) prescribe that, for a given return period, the general expression for IDF relationships should be written as

$$i = \frac{w}{\left(d + \theta\right)^{\eta}} \tag{2}$$

Rigorously, the coefficients *w*, θ, and η depend on the return period. However, because the IDF curves for different return periods cannot intersect each other, this dependence cannot be arbitrary. Actually, this restriction imposes bounds for the range of variation of parameters w, θ, and η. If $\{w_1, \theta_1$ e $\eta_1\}$ and $\{w_2, \theta_2$ e $\eta_2\}$ denote the parameter sets for return periods T_1 and T_2, respectively, with $T_2<T_1$, Koutsoyannis et al. (1998) suggest the following restrictions on the range of variation of parameters

$$\begin{aligned} &\theta_1 = \theta_2 = \theta \geq 0 \\ &0 < \eta_1 = \eta_2 = \eta < 1 \\ &w_1 > w_2 > 0 \end{aligned} \quad (3)$$

In this set of restrictions, it is worth to note the only parameter that can consistently increase with increasing return periods is w, which results in substantial simplification of equation (2). In fact, these arguments justify the formulation of the following general model for IDF relationships

$$i_{d,T} = \frac{a(T)}{b(d)} \quad (4)$$

which exhibits the advantage of expressing separable dependence relations between i and T, and between i and d. In equation (4), $b(d)=(d+\theta)^{\eta}$ with $\theta>0$ and $0<\eta<1$, whereas $a(T)$ is completely defined by the probability distribution function of the maximum rainfall intensities. The analytical form of equation (4) is consistent with most IDF equations estimated for many locations in Brazil and elsewhere [see, for instance, Wilken (1978), Pinheiro and Naghettini (1998), Chen (1983) and Raiford et al. (2007)].

Suppose that I_d denote the annual maximum rainfall intensity of duration d, defined as the ratio between the annual maximum total depth, abstracted for the time duration d, and the duration d itself. The random variable I_d has a cumulative probability function $F_d(i)$, which is given by

$$\Pr(I_d \leq i) = F_d(i) = 1 - \frac{1}{T_{(i)}} \quad (5)$$

where T represents the return period, in years, associated with the event.

Rainfall fields may show the property of 'simple scaling in the strict sense', which is formally defined by Menabde et al. (1999) by the expression

$$I_d \overset{dist}{=} \left(\frac{d}{D}\right)^{-\gamma} I_D \quad (6)$$

where the sign of equality refers to identical probability distributions in both sides of the equation, D denotes a duration $D>d$, usually taken as 24 hours, and γ is the scale factor which is supposed constant. As opposed to the simple scaling hypothesis, there is the general case of 'multiscaling', in which the factor $(d/D)^{-\gamma}$ is regarded as a random variable dependent upon the ratio (d/D). The simple scaling hypothesis, as defined by equation (6), can be empirically verified and, if accepted as true, be employed to construct simple disaggregation models of practical use.

Equation (6) may be rewritten in terms of the moments of order q about the origin, denoted by, $\langle I_d^q \rangle$ thus resulting the expression

$$\langle I_d^q \rangle = \left(\frac{d}{D}\right)^{-\gamma q} \langle I_D^q \rangle \quad (7)$$

or

$$d^{\gamma q} \langle I_d^q \rangle = D^{\gamma q} \langle I_D^q \rangle \quad (8)$$

According to Menabde et al. (1999), the only functional form of $\langle I_d^q \rangle$ capable of satisfying equation (8) is

$$\langle I_d^q \rangle = G(q)\, d^{-\gamma q} \quad (9)$$

where $G(q)$ is a function of q. This expression reflects the property of 'simple scaling in the wide sense', meaning that equation (9) is implied by equation (6) but not vice-versa. In the case of 'multiscaling', the exponent of d, as in equation (9), would have to be replaced by a non-linear function $K(q)$.

From equation (6), it follows that

$$F_d(i) = F_D\left[\left(\frac{d}{D}\right)^{\gamma} i\right] \quad (10)$$

For many parametric forms, equation (10) may be expressed in terms of a standard variate, as given by

$$F_d(i) = F\left(\frac{i-\mu_d}{\sigma_d}\right) \quad (11)$$

where $F(.)$ is a function independent of d. If that is the case, it follows from equation (10) that

$$\mu_d = \left(\frac{d}{D}\right)^{-\gamma} \mu_D \quad (12)$$

and

$$\sigma_d = \left(\frac{d}{D}\right)^{-\gamma} \sigma_D \quad (13)$$

By substituting expressions (11), (12), and (13) into equation (5) and inverting it with respect to i, one obtains

$$i_{d,T} = \frac{\mu_D D^{\gamma} - \sigma_D D^{\gamma} F^{-1}(1-1/T)}{d^{\gamma}} \quad (14)$$

By equaling equation (14) to the general model for IDF relationships, as in equation (4), it is easy to verify that

$$\gamma = \eta \tag{15}$$

$$\theta = 0 \tag{16}$$

$$b(d) = d^{\eta} \tag{17}$$

and

$$a(T) = \mu + \sigma F^{-1}(1 - 1/T) \tag{18}$$

where $\mu = \mu_D D^{\eta}$ and $\sigma = \sigma_D D^{\eta}$ are constants. It is worthwhile to note that the simple scaling hypothesis implies the equality between the scale factor γ and the exponent η, as in the expression relating rainfall intensities and durations.

The simple scaling property, as formalized by equation (9), can be empirically verified by replacing the population moments by the corresponding sample moments about the origin. On the other hand, in order to check the validity of equation (10), one needs to specify a probability distribution for the annual maximum rainfall intensities. In this context, two of the most frequently used probability distributions, namely the Generalized Extreme Value (GEV) and the EV1 or Gumbel parametric models, are examples of functional forms that are compatible with expression (11) and appropriate for the empirical verification of equation (10).

4. APPLICATION OF SIMPLE SCALING PROPERTIES

The adequacy of the simple scaling model to IDF estimation, as prescribed by equation (14), can be verified through the use of sub-daily data from recording gauging stations. However, because sub-daily rainfall intensity data were not available at the Uberaba gauging station, the studies concerning the scale invariance properties were performed for four recording gauging stations located in different regions, within the state of Minas Gerais, in order to make possible transferring the rainfall information to the site of interest. These stations are: Vespasiano (code ANA 01943009), in the metropolitan region of the state capital Belo Horizonte; Papagaios (code ANA 01944049); Lagoa do Gouvea (code ANA 01845004); and Entre Rios de Minas (code ANA 02044007), all of them located in the upper São Francisco river basin, which borders, on the northeast side, the Grande river watershed, where Uberaba is situated.

Taking into account (i) that the main simple scaling properties, namely, the exponent η, as in equation (15), and the durations for which these properties prevail, did not show much variation among the stations (Naghettini, 2000); (ii) that the gauging station of Vespasiano, as opposed to the other three sites, is located within a micro-region with less pronounced relief, which roughly approximates the orographic features found in Uberaba; and (iii) that are available 18 years of rainfall data for the durations 10 min, 15 min, 30 min, 45 min, 1, 2, 3, 4, 8, 14 e 24 hours at the Vespasiano gauging station, the decision was to apply the scale invariance model to this station and then combine the results with the daily rainfall data available at Uberaba in order to derive the local IDF relationship. The application of scale invariance model to Vespasiano rainfall data is the object of the paragraphs to follow.

The verification of the simple scaling model can be done by using the sample moments in equation (9), with γ=η. Figure 3 illustrates the association of $\langle I_d^q \rangle$ with *d*, both in logarithmic space, for moment orders *q*=1, 2, and 3. Note that for all orders *q*, there are well defined scale relationships for durations from 1 to 24 hours; the durations smaller than 1 hour exhibit the same property, but with a distinct slope. In fact, the regressions between moments and durations, in logarithmic coordinates, conform better to linearity when they are separated in a first subset for durations from 24 hours down to 1 hour, and a second subset for sub-hourly durations. Figures 4 and 5 depict the scatter plots and the regression results for subsets of durations from 24 to 1 hour and from 1 hour to 10 minutes, respectively. In both cases, it is evident the linear fit conforms better for two distinct subsets than for the entire set of durations.

By representing the exponent of *d* in equation (9) by $K(q) = -\eta q$ and using the coefficients of the regressions between log [$\langle I_d^q \rangle$] and log (*d*), valid for the two subsets of durations, it is clear from Figures 6 and 7, the relations between *K*(*q*) and *q* are very closely linear. The linearity of these relations is an argument to confirm the hypothesis of simple scale invariance in a wide sense, as formalized by equation (9), for the two subsets of durations. The angular coefficient of the linear regression between *K* (*q*) and *q* gives the following estimates of the scale factor: $\acute{\eta}$ = 0,7398, for durations from 1 hour to 24 hours, and $\acute{\eta}$ = 0,5681, for sub-hourly durations, with an intersection point exactly at *d*=1 hour. The derivation of IDF estimates from 24-hour rainfall can be accomplished by using equation (14), with $\gamma = \acute{\eta} = 0{,}7398$ and with the estimates of μ_D and σ_D, for *D*=24 hours. For sub-hourly durations, the procedure is identical, this time with γ=$\acute{\eta}$=0,5681 and with the estimates μ_D and σ_D for *D*=1 hour. It is worth to remark that μ_D and σ_D represent respectively the location and scale parameters of the probability distribution fitted to the rainfall intensities of duration *D.* Taking as an example the Vespasiano gauging station, where the Gumbel distributions fits well the rainfall intensities of 24 hours with parameters μ_{24}=3,17mm/h and σ_{24}=1,1333 mm/h, it is easy to see, by employing the Gumbel inverse function in

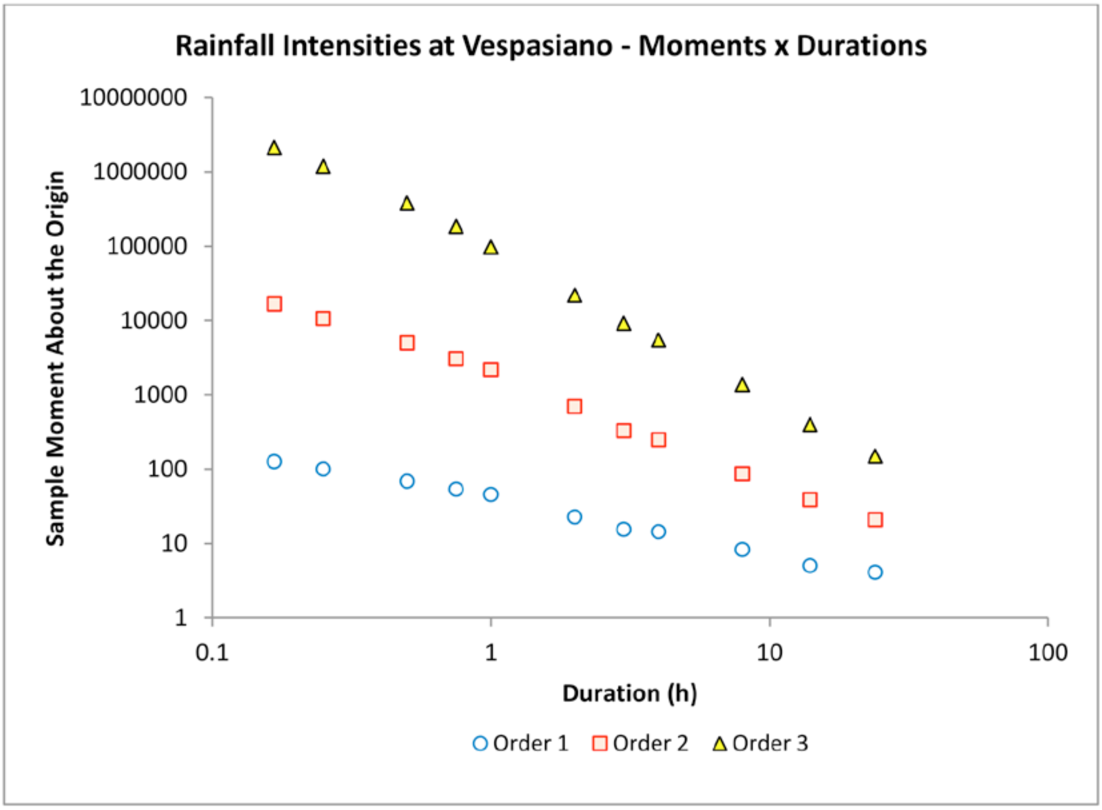

Figure 3 – Sample moments of order q versus durations, for sub-daily annual maximum rainfall intensities recorded at Vespasiano. (10 min ≤ d ≤ 24 h)

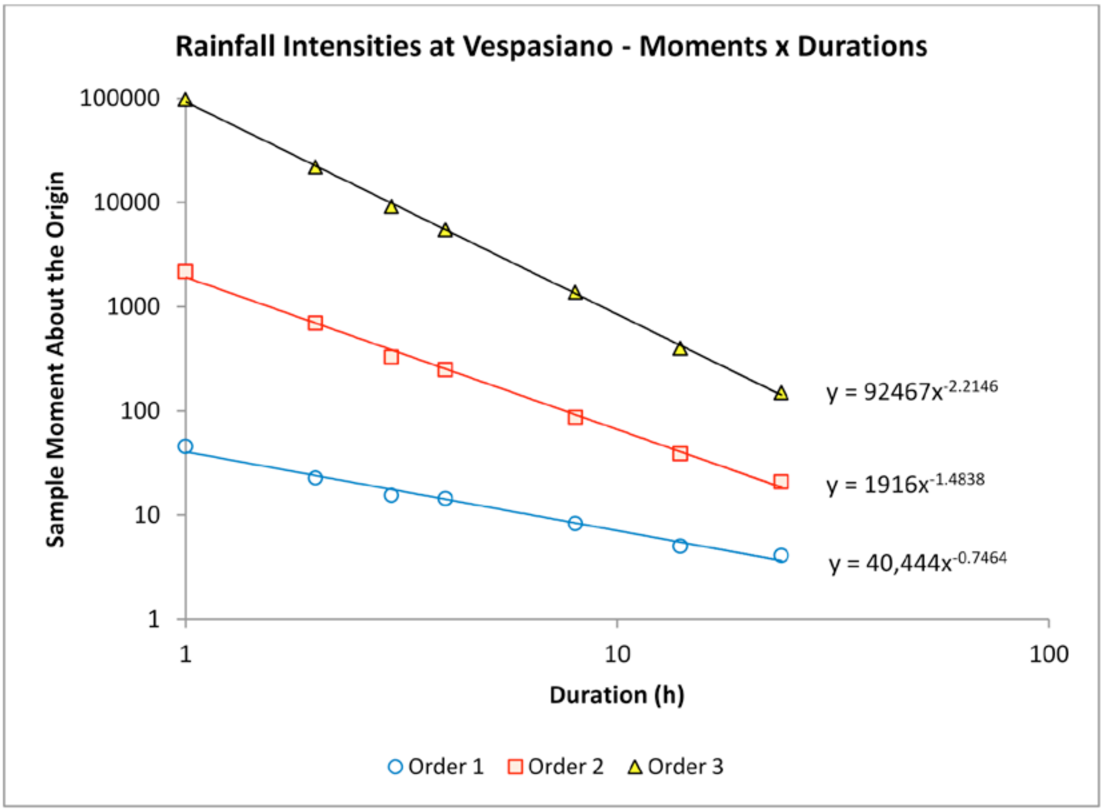

Figure 4 – Sample moments of order q versus durations, for sub-daily annual maximum rainfall intensities recorded at Vespasiano. (1 h ≤ d ≤ 24 h)

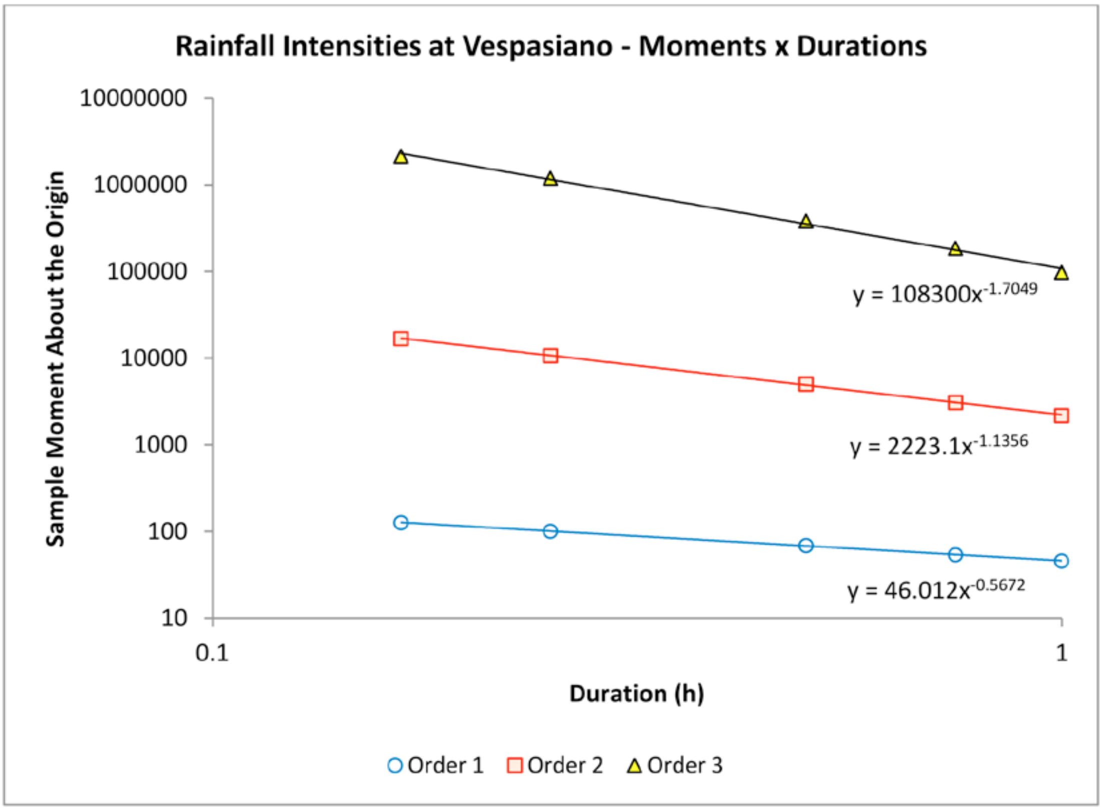

Figure 5 – Sample moments of order q versus durations, for sub-daily annual maximum rainfall intensities recorded at Vespasiano. (10 min ≤ d ≤ 1 h)

equation (14), that the corresponding IDF estimates for durations in the range of 1 h to 24 h, should be given by

$$i_{d,T} = \frac{28.4 - 10.16\,ln\left[-\,ln\left(1 - 1/T\right)\right]}{d^{0.7398}} \tag{19}$$

This is the essence of applying the simple scale invariance model to IDF estimation. On the basis of the arguments provided, the strategy to derive the IDF relationship for Uberaba comprehends the following steps:

- From the relief characteristics of Vespasiano and from the small spatial variability of the scale factors within the region under study [for instance, the scale factors, as calculated by Naghettini (2000), for durations larger than 1 hour for the sub-daily data observed at Papagaios (01944049), at Lagoa do Gouvea (01845004), and at Entre Rios de Minas (02044007) were 0.75, 0.77, and 0.81, respectively], it seems plausible to admit as valid, also for Uberaba, the following estimates for the scale factor: ή=0,7398, for durations from 1 hour to 24 hours, and ή=0,5681, for sub-hourly durations;
- From the series of annual maximum daily rainfall intensities, observed at the gauging station of Uberaba (INMET 83577), the second step is to build the series of annual maximum 24-hour rainfall intensities, by multiplying the first one by the factor 1.14, as recommended by DAEE/CETESB (1980), as the empirical ratio between 24-hour and daily rainfall depths averaged among a large number of sites;
- The next step is to fit a parametric probability model, which should be compatible with the inherent assumptions of simple scaling invariance, such as Gumbel, Log-Normal, or GEV (Generalized Extreme Value) distributions, to the annual maximum 24-hour rainfall intensities as built in the previous step; and
- Finally, to derive the IDF relationship for the location of Uberaba, by using equation (14) first for durations from 24-hour down to 1-hour, with the scale factor ή=0,7398, and next, for durations from 1 hour to 10 minutes, with the scale factor ή=0,568, both with an intersection point at *d*=1 hour.

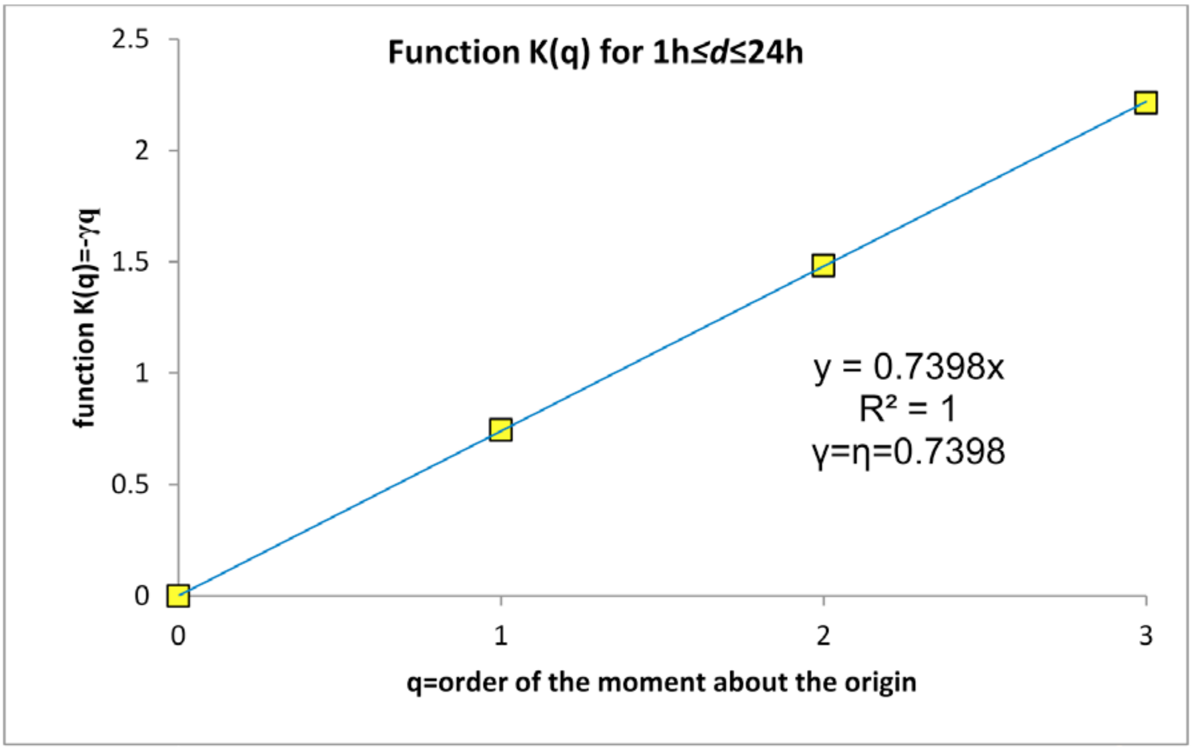

Figure 6 – Function K(q)=-γq for the sample moments of order q of rainfall intensities of durations from 1 h to 24 h, at the Vespasiano gauging station.

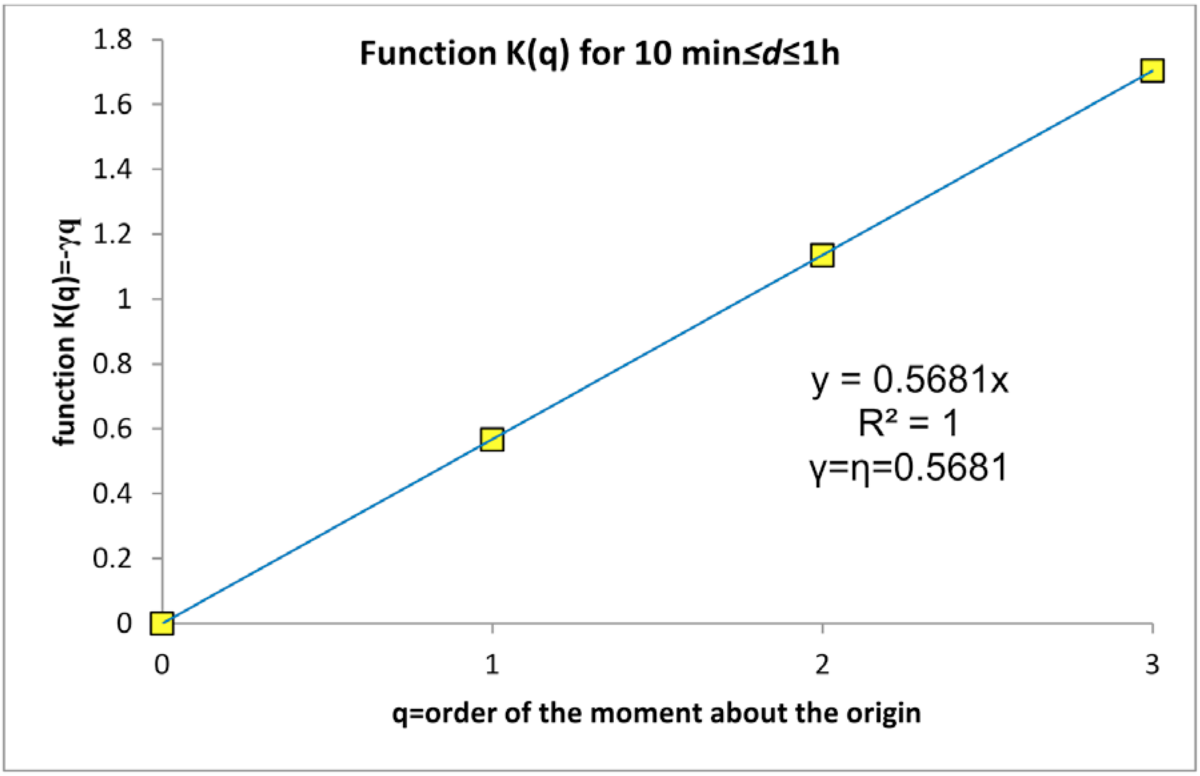

Figure 7 – Function K(q)=-γq for the sample moments of order q of rainfall intensities of durations from 10 min to 1 h, at the Vespasiano gauging station.

5 – FREQUENCY ANALYSIS OF ANNUAL MAXIMUM 24-HOUR RAINFALL INTENSITIES

Table 1 presents some descriptive statistics for the 80 values of annual maximum 24-hour rainfall intensity (mm/h), as calculated by the multiplication of the daily series, available at the gauging station of Uberaba from 1914 to 2012, by the factor 1.14. Figure 8 depicts the histogram of the available sample, with 13 class intervals.

Table 1 – Descriptive statistics for the sample of annual maximum 24-hour rainfall intensities at Uberaba. Except for dimensionless quantities, units are mm/h.

N	**80**	**3rd Quartile**	**4.212**
Mean	3.703	Maximum	7.458
Std. Deviation	1.029	Range	5.928
Coeff. Of Variation	0.278	Inter-quartile Range	1.233
Minimum	1.529	Mode	4.161
1st Quartile	2.979	Skewness	1.046
Median	3.548	Kurtosis	1.651

The sample of annual maximum 24-hour rainfall intensities has been submitted to a preliminary analysis for detecting possible serial dependence, heterogeneity, and outliers, respectively, through the statistical significance tests of Wald-Wolfowitz, Mann-Whitney and Grubbs-Beck. The null hypothesis of statistical independence cannot be rejected at 5% significance level (Wald-Wolfowitz test statistic=0.0012 with p-value=0.4995). The hypothesis of homogeneity also cannot be rejected at α=5% (Mann-Whitney test statistic=-1.887 with p-value=0.0296). However, as the presence of outliers is concerned, the Grubbs-Beck test, at α=5%, identified the 1969 rainfall intensity of 1.53 mm/h as a low outlier; no high outlier was identified. Since a low outlier can potentially affect the upper-tail estimation, which is the main focus of this work, the 1969 value has been withdrawn from the sample.

In the sequence, 2-parameter probability models, such as Exponential, Gumbel, and Log-Normal, as well as 3-parameter models, such as GEV, Pearson III, and Log-Pearson III, have been fitted to the sample by using the method of moments. All fitted models have passed the Kolmogorov-Smirnov (KS) and Chi-squared (χ^2) goodness-of-fit tests at the 5% significance level. On an exponential probability paper, the best fits were achieved by the GEV and the Gumbel probability distributions (Figure 8). The

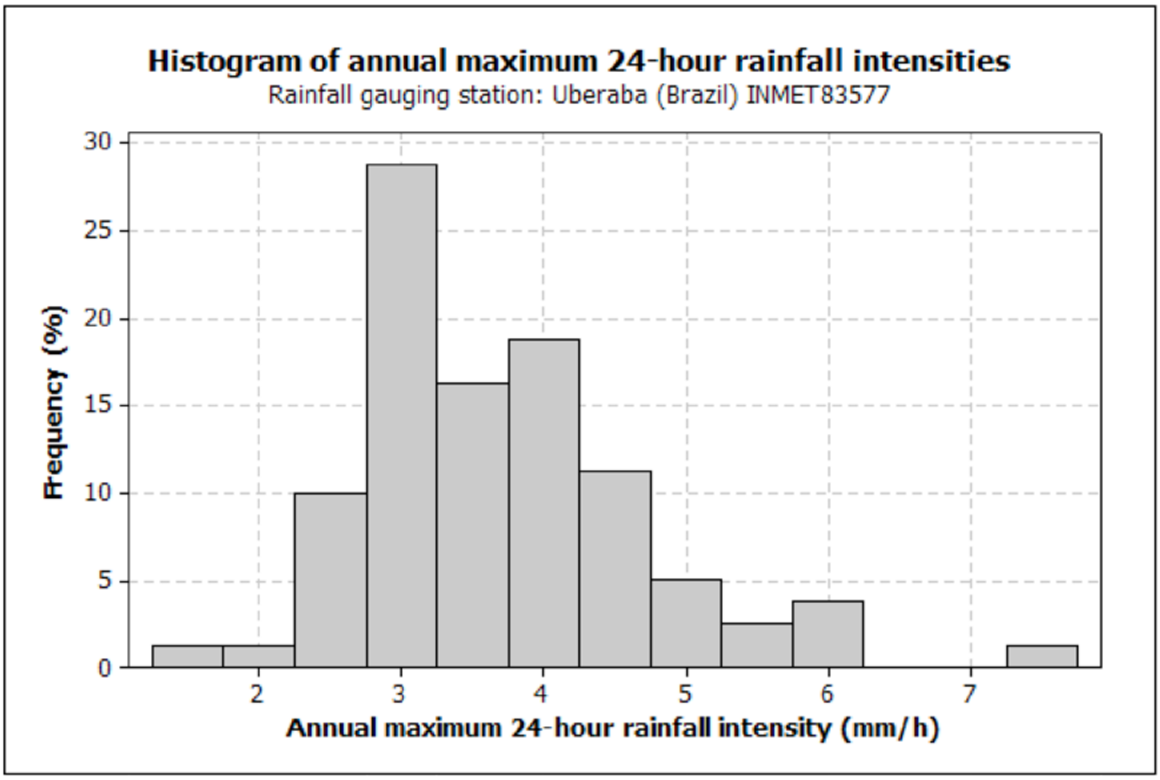

Figure 8 – Histogram of annual maximum 24-hour rainfall intensities at Uberaba.

goodness-of-fit statistics for the GEV model were KS statistic=0.0798, with p-value=0.6781; χ^2=10.7314 with p-value=0.903 and 5 degrees of freedom, whereas for the Gumbel distribution, they were KS statistic=0.0794, with p-value=0.6831; χ^2=10.7417 with p-value=0.950 and 6 degrees of freedom. Figure 9 shows a chart with the empirical frequency curve, and the fitted GEV and Gumbel models, along with their respective 95% confidence intervals.

The Gumbel distribution, as fitted by the method of moments, with parameter estimates $\hat{a} = 0{,}784$ and $\hat{a} = 3{,}278$, has been selected as the best-fit model. The selection of this model was based on the following arguments: (i) the Gumbel model provides a very good fit to empirical data; (ii) the Gumbel and GEV quantiles are almost identical to each other, for return periods up to 200 years; (iii) the 2-parameter Gumbel model is more parsimonious, in the statistical sense, than the 3-parameter GEV model; (iv) the Gumbel fit has narrower confidence intervals than those yielded by the GEV distribution; and (v) it is consistent with the simple scaling formulation given by equation (14).

6 – ESTIMATING THE IDF RELATIONSHIP FOR UBERABA – PROCEDURES AND RESULTS

The Gumbel distribution has as probability density function the expression

$$f_X(x) = \alpha \exp\left\{-\alpha(x-\beta) - \exp\left[-\alpha(x-\beta)\right]\right\}$$

$$-\infty < x < \infty, -\infty < \beta < \infty \text{ e } \alpha > 0 \qquad (20)$$

and its cumulative probability function is given by

$$F_X(x) = exp\left[-exp\left(-\frac{x-\beta}{\alpha}\right)\right] \qquad (21)$$

where α and β are scale and location parameters, equivalent, in equation (14), to σ_D and μ_D, respectively. Replacing F^{-1} in equation (14) by the Gumbel inverse function, with the usual parameter notation, in terms of the return period T, one can write

$$i_{d,T} = \frac{\beta_D D^\eta - \alpha_D D^\eta \, ln[-ln(1-1/T)]}{d^\eta} \qquad (22)$$

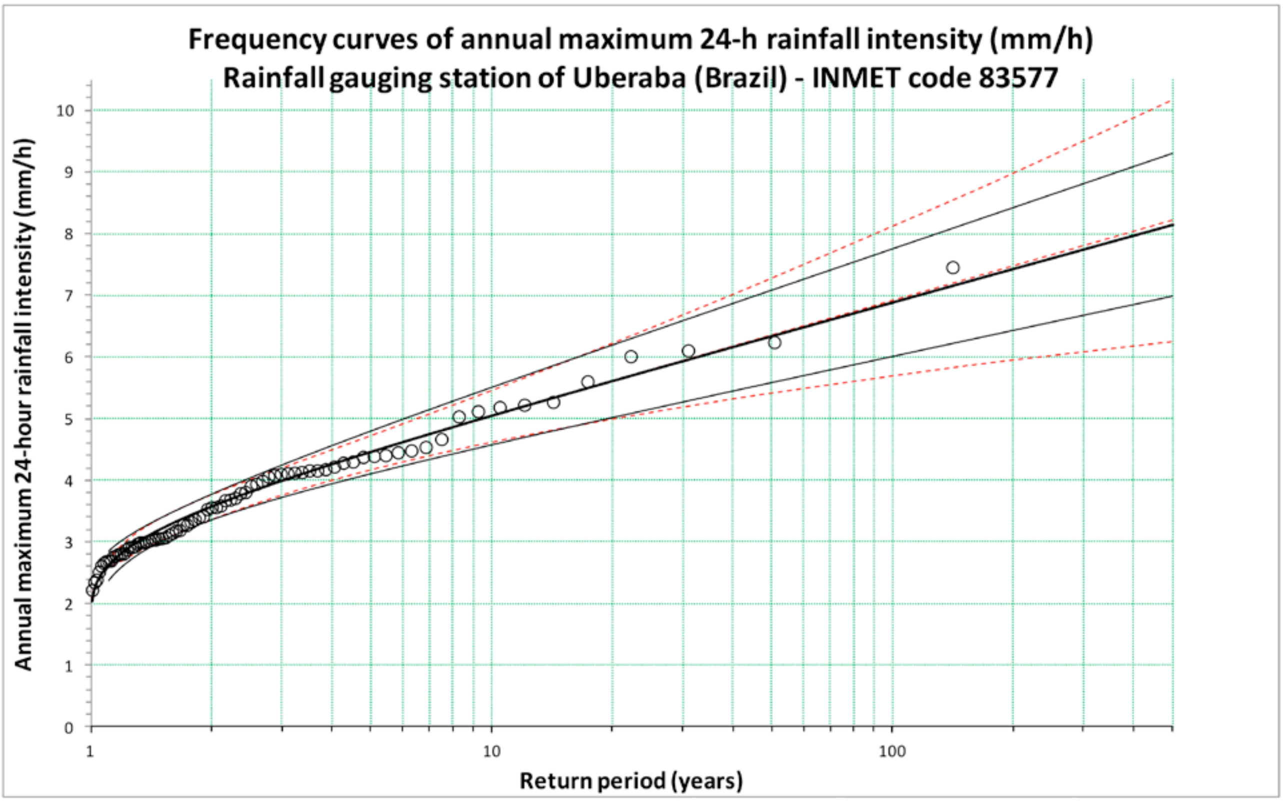

Figure 9 – Gumbel and GEV fits to the sample of annual maximum 24-hour rainfall intensities at the gauge of Uberaba. Gumbel quantiles and 95% confidence intervals are marked in solid lines. GEV quantiles and 95% confidence intervals are marked in dashed lines. Gringorten plotting positions were used for empirical frequencies.

Equation (22) is the key expression for deriving the IDF relationship for sub-daily durations. For the case of Uberaba, initially with D=24 h, $\hat{\alpha}=0,784$, $\beta=3,278$, $\hat{\eta}=0,7398$, and 1h ≤ d ≤ 24 h, the IDF equation for durations between 24 hours and 1 hour is given by

$$i_{d,T} = \frac{34,410 - 8,230\ln\left[-\ln\left(1 - 1/T\right)\right]}{d^{0,7398}} \quad (23)$$

where $i_{d,T}$ represents the intensity in mm/h, of a rainfall of duration d (in hours) and return period T (in years). Analogously, this time with D=1 h, $\hat{\alpha}=8,230$, $\beta=34,410$, $\hat{\eta}=0,5681$, and 0,1667 h ≤ d ≤ 1 h, the IDF equation for sub-hourly durations equal or larger than 10 minutes (0,1667 h) is given by

$$i_{d,T} = \frac{34,410 - 8,230\ln\left[-\ln\left(1 - 1/T\right)\right]}{d^{0,5681}} \quad (24)$$

where $i_{d,T}$ represents the intensity in mm/h, of a rainfall of duration d (in hours) and return period T (in years).

The IDF relationships, as given by equations (23) e (24), had their results compared to those estimated by three other procedures:

- Equation $i_{d,T} = (d+20)^a\left[b + c\,ln(T - 0,5)\right]$, where a=-0,849, b=19,18 e c=5,37 for 10 min ≤ d ≤ 60 min, and a=-0,834, b=17,78 and c=4,98 for 60 min ≤ d ≤ 1440 min, as reported by DAEE/CETESB (1980) for the recording gauging station of Barretos, located in the state of São Paulo, with latitude 20°33' south and longitude 48°34' west, code INMET 83625, and intensities expressed in mm/min and duration in minutes;
- Equation $i_{d,T} = 2400T^{0,164}/(d + 31,194)^{0,867}$ for the location of Uberaba, defined by Freitas et al. (2001), by interpolating rainfall data from several recording gauging stations located in the state of Minas Gerais, with intensities expressed in mm/h and durations in minutes; and Tables of intensity, duration, and frequency for the location of Catalão, in the state of Goiás, with latitude 18°10' south and longitude 47°58' west, defined by Pfafstetter (1957) and reproduced in DAEE/CETESB (1980).

Tables 2, 3, 4, and 5 show the comparison among the results, as obtained by the equations deduced in this paper and by each of the previously mentioned procedures, for return periods T=2, 25, 50, and 100 years, respectively. Figures 9 to 12 illustrate the graphical comparison among the results from Tables 2 to 5. The tables and figures show the results from the IDF relationships described in here are in between those estimated for the locations of Barretos and Catalão, with moderate percent differences. Concerning the results from the equation proposed by Freitas et al. (2001), they are systematically larger than those yielded by equations (23) and (24), particularly for durations larger than 30 minutes, with relative percent errors ranging from 1.0 to 56.2%.

Table 2 – Comparison among the IDF relationships proposed for Uberaba, for *T*=2 years.

1	2	3	4	5	6	7	8
Duration (h)	**Eqs. (23) and (24)(mm/h)**	**Eq. Barretos (mm/h)**	**2/3**	**Freitas et al. (2001) (mm/h)**	**2/5**	**Eq. Catalão (mm/h)**	**2/7**
0.1667	103.56	71.39	1.45	107.03	0.97	115.08	0.90
0.5	55.49	46.27	1.20	75.95	0.73	63.96	0.87
1	37.43	31.04	1.21	53.74	0.70	41.34	0.91
2	22.41	19.27	1.16	34.67	0.65	25.62	0.88
4	13.42	11.50	1.17	20.89	0.64	15.48	0.87
8	8.04	6.66	1.21	12.06	0.67	9.24	0.87
14	5.31	4.24	1.25	7.59	0.70	6.06	0.88
24	3.57	2.73	1.31	4.82	0.74	4.08	0.87

Table 3 – Comparison among the IDF relationships proposed for Uberaba, for *T*=25 years.

1	2	3	4	5	6	7	8
Duration (h)	Eqs. (23) and (24) (mm/h)	Eq. Barretos (mm/h)	2/3	Freitas et al. (2001) (mm/h)	2/5	Eq. Catalão (mm/h)	2/7
0.1667	168.05	121.52	1.38	161.96	1.04	159.06	1.06
0.5	90.04	78.76	1.14	114.92	0.78	93.72	0.96
1	60.73	52.85	1.15	81.32	0.75	63.36	0.96
2	36.37	32.81	1.11	52.46	0.69	40.26	0.90
4	21.78	19.58	1.11	31.61	0.69	24.84	0.88
8	13.04	11.34	1.15	18.24	0.72	14.88	0.88
14	8.62	7.22	1.19	11.49	0.75	9.36	0.92
24	5.79	4.64	1.25	7.30	0.79	6.24	0.93

Table 4 – Comparison among the IDF relationships proposed for Uberaba, for *T*=50 years.

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Duration (h)	**Eqs. (23) and (24) (mm/h)**	**Eq. Barretos (mm/h)**	**2/3**	**Freitas et al. (2001) (mm/h)**	**2/5**	**Eq. Catalão (mm/h)**	**2/7**
0.1667	184.07	134.15	1.37	181.46	1.01	172.50	1.07
0.5	98.63	86.94	1.13	128.76	0.77	103.26	0.96
1	66.52	58.34	1.14	91.11	0.73	70.74	0.94
2	39.84	36.22	1.10	58.77	0.68	45.24	0.88
4	23.85	21.61	1.10	35.42	0.67	28.08	0.85
8	14.29	12.53	1.14	20.44	0.70	16.80	0.85
14	9.44	7.97	1.19	12.88	0.74	10.98	0.86
24	6.34	5.13	1.24	8.17	0.78	7.26	0.87

Table 5 – Comparison among the IDF relationships proposed for Uberaba, for *T*=100 years.

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Duration (h)	**Eqs. (23) and (24) (mm/h)**	**Eq. Barretos (mm/h)**	**2/3**	**Freitas et al. (2001) (mm/h)**	**2/5**	**Eq. Catalão (mm/h)**	**2/7**
0.1667	199.97	146.68	1.36	203.31	0.98	186.72	1.07
0.5	107.14	95.06	1.13	144.26	0.74	113.58	0.94
1	72.27	63.79	1.13	102.08	0.71	78.72	0.92
2	43.28	39.61	1.09	65.85	0.66	50.76	0.85
4	25.92	23.63	1.10	39.68	0.65	31.62	0.82
8	15.52	13.70	1.13	22.90	0.68	18.96	0.82
14	10.26	8.71	1.18	14.42	0.71	12.36	0.83
24	6.89	5.60	1.23	9.16	0.75	8.16	0.84

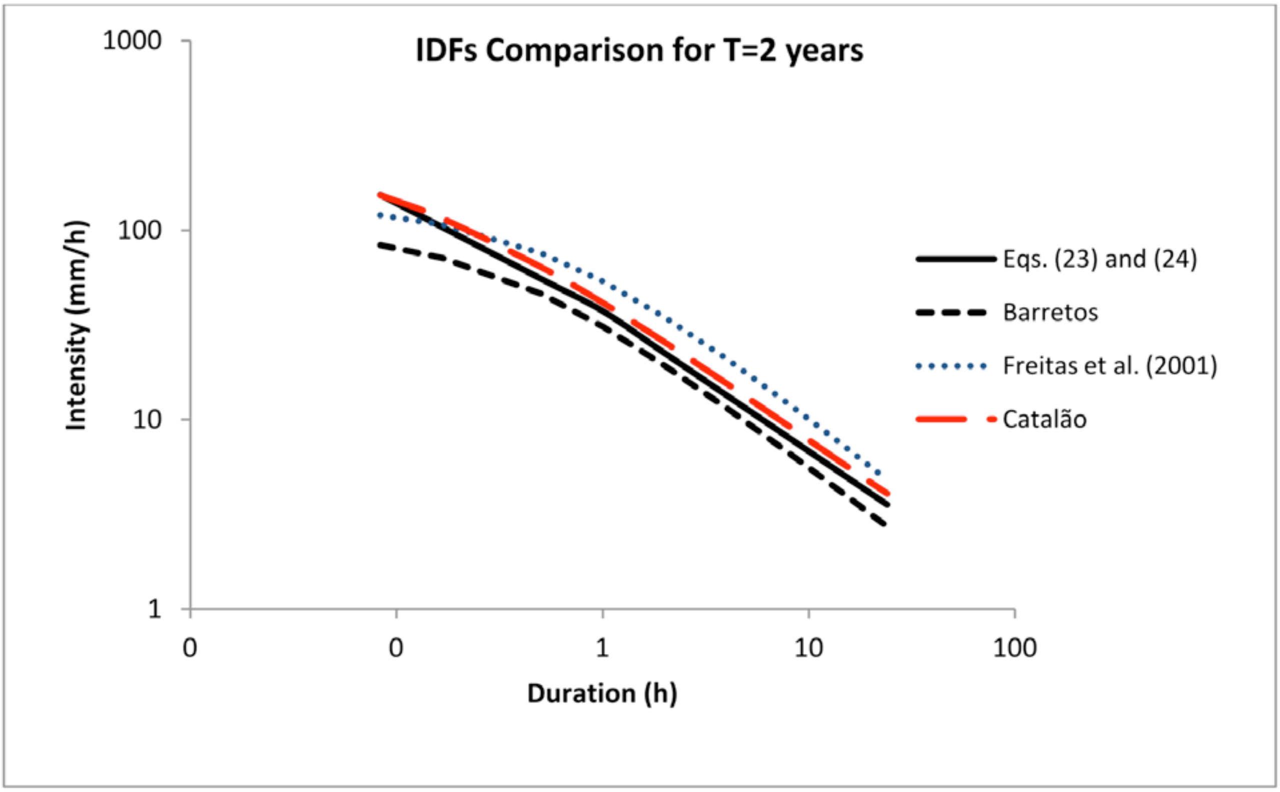

Figure 10 – Comparison among IDF relationships for *T*=2 years.

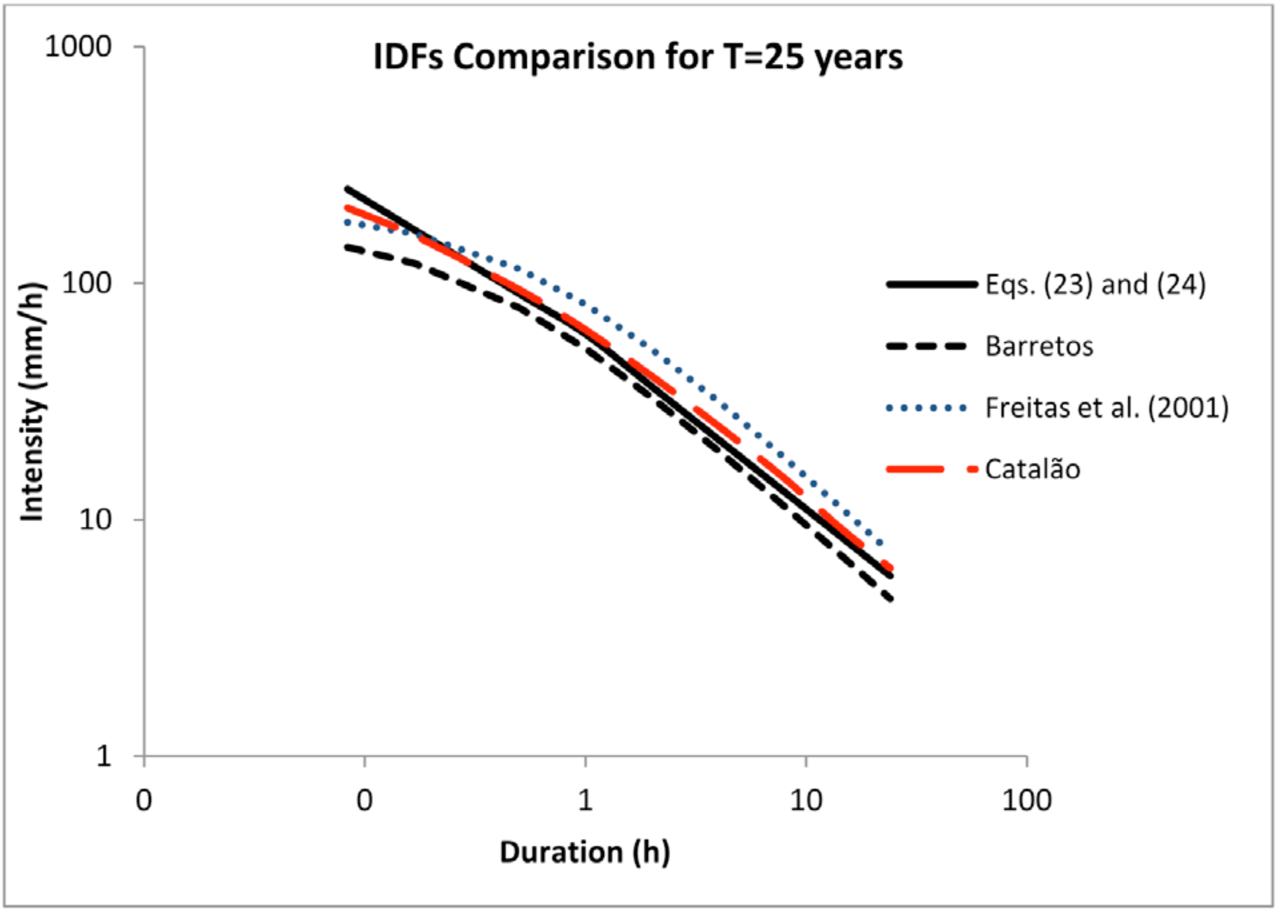

Figure 11 – Comparison among IDF relationships for *T*=25 years.

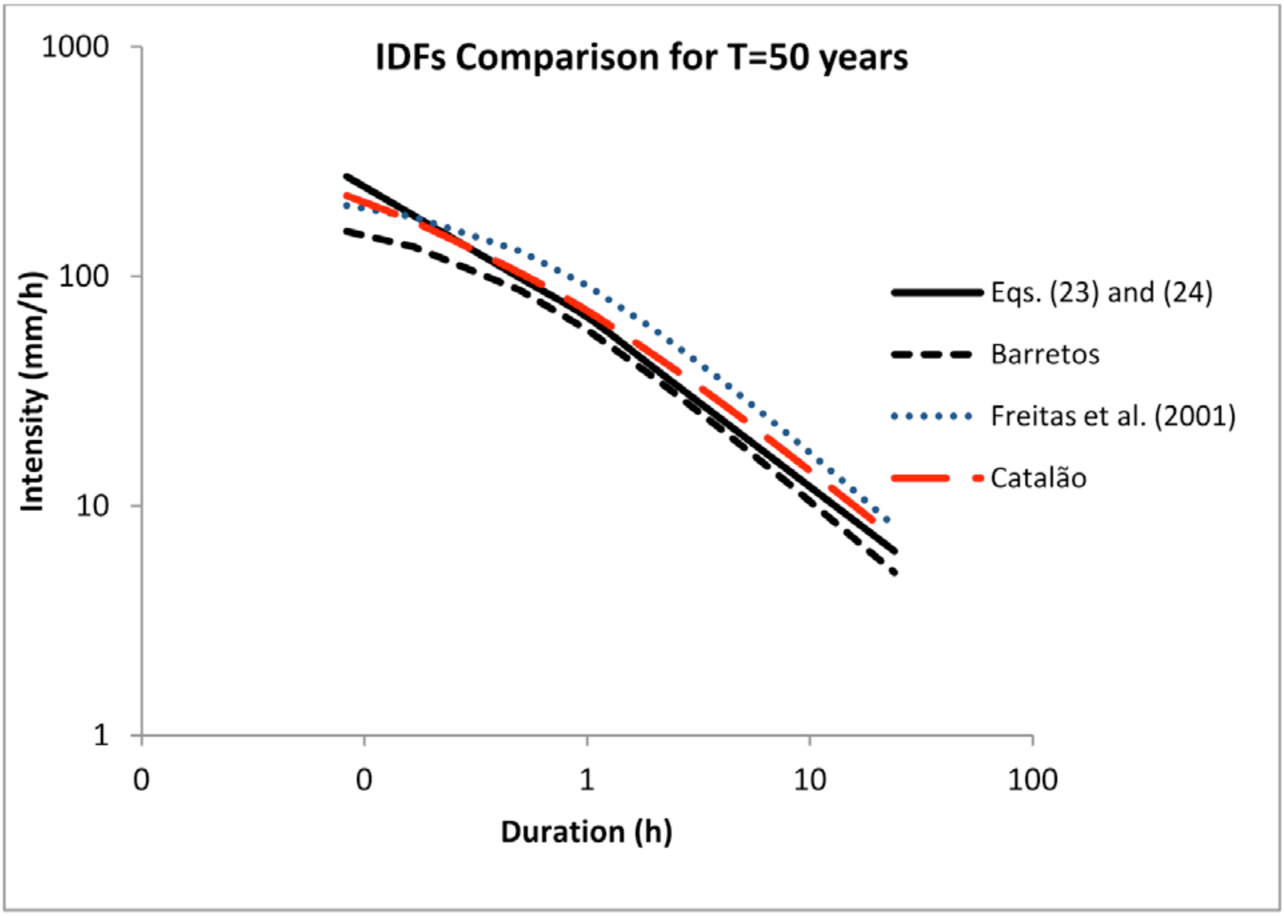

Figure 12 – Comparison among IDF relationships for *T*=50 years.

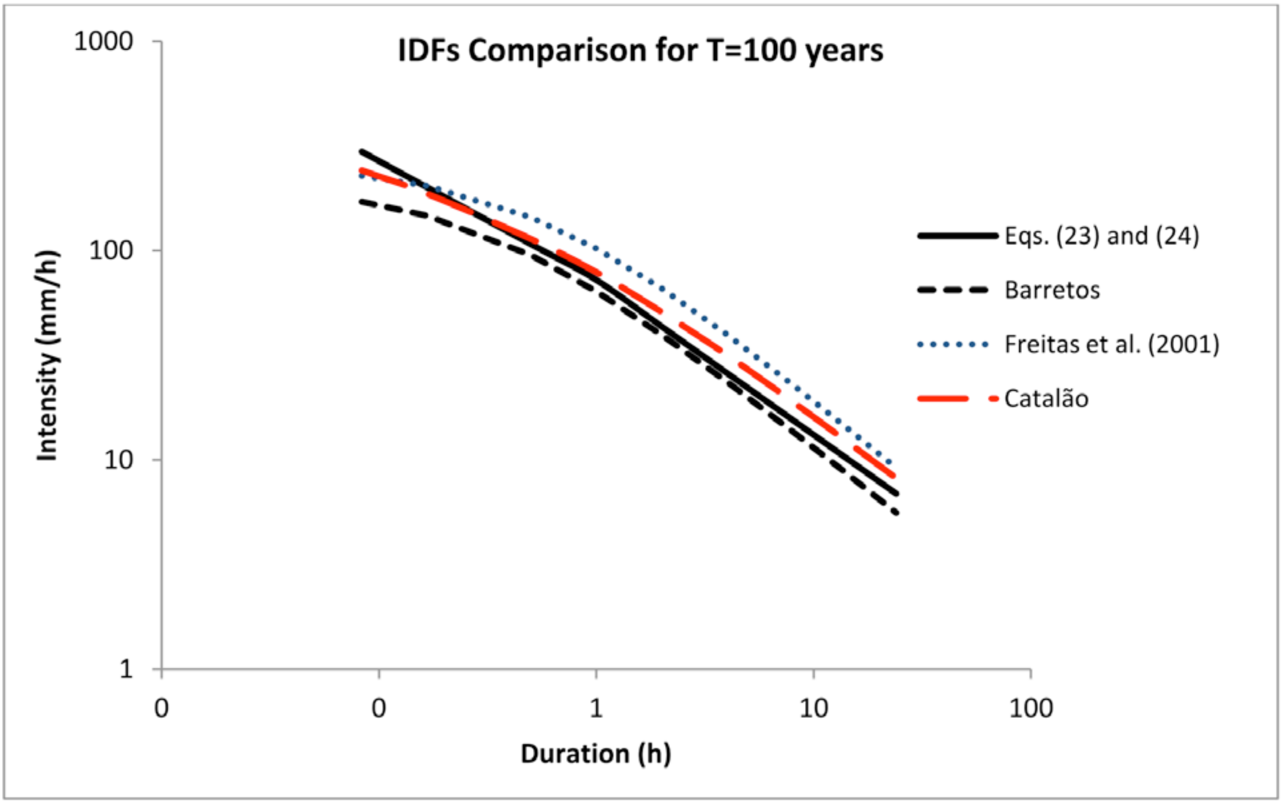

Figure 13 – Comparison among IDF relationships for *T*=100 years.

7 – ANALYSIS OF THE RESULTS AND CONCLUSIONS

The IDF relationships as estimated in here for the town of Uberaba, formalized by equations (23) and (24), were based on the scale invariance properties, first, for durations from 24 hours to 1 hour, and, then, for durations from 1 hour to 10 minutes. In general, these distinct ranges of durations also indicate significant differences in the prevalent mechanisms of uplifting air masses in the atmosphere, thus often leading to rainfall of the convective type or of the frontal type. Therefore, from this viewpoint, it seems coherent the scale inflection between these ranges of durations, as proposed in this paper.

The deduction of IDF relationships for Uberaba from numerical scale factors estimated for the location of Vespasiano, can be justified by the relatively small variability of these factors, as observed from estimates for other rainfall recording gauging stations situated in the state of Minas Gerais (Naghettini, 2000). In addition, the series of short-duration rainfall rates recorded at the four recording gauging stations considered in here, are consistent with the scale inflection point placed at the duration of 1 hour. These empirical evidences and the arguments from the scale invariance theory provided grounds for deducing IDF estimates from at-site daily rainfall depths recorded at the gauging station of Uberaba. However, since the scale factor η and parameters μ and σ, as in equation (22), may be interpreted as regional climatic characteristics (Menabde, 1999), further in-depth work is needed to elucidate possible covariation between η and climatic and/or relief variables.

The comparison with the results obtained for locations relatively close to Uberaba, like Barretos (north of São Paulo state) and Catalão (south of Goiás state), suggests a certain coherence for the macro-region where Uberaba is placed, known as “Triângulo Mineiro”, bordered on the south by the state of São Paulo and on the north by the state of Goiás. The IDF estimates for Uberaba are relatively close and intermediate between the ones valid for Barretos and Catalão. The IDF estimates resulting from the equation by Freitas et al. (2001), obtained from interpolation among point estimates over a large area, depart significantly from the other results and, thus, seem to be inconsistent.

It is worth to remind, however, this is a preliminary study motivated by the unavailability of at-site sub-daily rainfall data, of adequate time span, at the Uberaba gauging station. In order to check the model of simple scaling for IDF estimation and its results, it is absolutely necessary to install rainfall recording gauging stations in the urban and peri-urban areas of Uberaba, and, once adequate samples of sub-daily rainfall data become available, to proceed with regional frequency analysis of maximum records, by contemporary methods such as the L-Moment procedures described in Hosking and Wallis (1997). Future sub-daily records would eventually provide evidences to further understand the properties of scale invariance, in the context of IDF estimation, and to relate them to local climate and relief characteristics in a more meaningful way.

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FLOOD-RELATED RISK EDUCATION AND COMMUNICATION

EDUCACIÓN Y COMUNICACIÓN SOBRE RIESGOS ASOCIADOS A INUNDACIONES.

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Abstract

While flood disasters result from the interaction of natural and human factors, the human dimension is still sometimes underemphasized in flood management. This paper discusses the role of non-structural measures for flood management processes, such as risk preparedness, emergency responses and rehabilitation. Specific emphasis is given to the role of human capacities, in particular water-related risk education, training and communication, on the mitigation of flood impacts. Flood risk education (at the primary, secondary and community levels, as well as at the technical and higher levels) and communication strategies (actors, channels and message content) provide a valuable contribution to the social dynamics of flood risk perceptions, preparedness and vulnerability. This study further highlights the importance of active stakeholder participation before, during and after flood events, as well as the integration of general public perceptions in flood damage analysis and risk management.

Keywords: Flood, risk perception, risk management, human capacities, education, communication, training.

Resumen

A pesar de que los desastres por inundaciones sean resultado de factores naturales y humanos, su dimensión humana está todavía a menudo subestimada. Este artículo analiza el papel de medidas no estructurales dentro de los procesos de gestión de inundaciones como preparación de riesgos, respuestas de emergencia y rehabilitación. Se da un énfasis específico al papel de las capacidades humanas, en particular la educación, entrenamiento y comunicación de riesgo, en la mitigación del impacto de inundaciones. La educación de riesgos asociados a inundaciones (en los niveles primario, secundario y comunitario, así como los técnicos y superiores) y las estrategias de comunicación (actores, medios y contenido de mensajes) ofrecen una contribución valiosa para las dinámicas sociales de percepción, preparación, capacidad y vulnerabilidad de riesgos de inundación. Este artículo subraya la importancia de la participación activa de los actores envueltos antes, durante y después de los eventos de inundación, así como la integración de las percepciones del público en general en el análisis de daños por inundaciones y en la gestión de riesgo.

Palabras clave: Inundación, percepción de riesgo, gestión de riesgo, capacidades humanas, educación, comunicación, entrenamiento.

INTRODUCTION

Floods were responsible for 43% of recorded disasters from 1992 to 2001, affecting over 1.2 billion people worldwide (WWAP-UNESCO 2009). Flooding can seriously disrupt human societies via a series of impacts, which include loss of human life, health hazards, damage to property, and the disruption of transportation systems, water supply, sewage systems and power supply. Floods can be particularly devastating in developing countries, which are less prepared to cope with disasters (WWAP-UNESCO 2009). In addition, the poor suffer most of the burden, as they lack capacity to prepare and respond to natural disasters.

The traditional perspective that floods are entirely natural disasters has been challenged over the last decades. While strongly associated with natural factors, such as rainfall, topography and runoff processes, the impact of flood hazards is conditioned by human behaviour and vulnerability. An early study of the responses of two separate communities to the same transboundary flood event found deep differences in terms of flood impacts due to differences in the political, social structure and cultural values of these communities that are reflected in different levels of vulnerability (Clifford 1956). Human vulnerability can be defined as “a condition or process resulting from physical, social, economic and environmental factors, which determines the likelihood and scale of damage from the impact of a given hazard” (UNDP 2004). The human dimension of floods embraces a series of components, from stormwater management and institutional capacities, to household preparedness and emergency responses, among others. These non-structural components rely on human capacities, in terms of education, training and communication (Szöllösi-Nagy and Zevenbergen, 2005). Even if floods cannot be entirely prevented, flood preparedness, emergency planning and adaptation can significantly mitigate their consequences to a considerable extent. These rely on human capacities, both

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at the public and private levels, and are conditioned by education, training and communication. and precautionary flood preparedness.

Other human-related factors that contribute to flooding are land use changes such as urbanization and deforestation of the catchment basin. Urbanization implies the transformation of natural land surfaces into impervious surfaces that block the percolation of water into soil. This has important effect on stormwater hydrology, due to the increase in runoff volumes and peak discharges. The increased flow velocity of water over the surface leads to a higher frequency of flash floods, with higher associated casualties and property damages. The period of rapid urbanization that was observed during the last decades is likely to contribute to an increase in urban floods. For the first time in human history, most of the world's population now lives in urban areas. Unplanned occupation, unsustainable planning and building practices, which are often associated with rapid urbanization, can further magnify flood risks (Szöllösi-Nagy and Zevenbergen, 2005). In addition, rapid urbanization has also lead to the significant increase of peri-urban areas, which can be significantly vulnerable to floods. For instance, as noted by Tucci and Villanueva (2005), flood impacts in urban areas are often associated with population settlements established during dry years on flood plains and hill slopes combined with the increase of impervious areas. .

Andjelkovic (2001) suggested a characterization of flooding aspects that are differently addressed for rural and urban conditions:

- climatic aspects: "deals with the climatic conditions that may lead to the occurrence of floods. In urban conditions, short and intensive showers proved to be just as critical as long lasting rains, but in rural conditions long lasting rains over an area-wide territory, accompanied with snow melting in the river basin, are recognised as possibly more influential."
- social aspects: "deals with the way the floods occur in different settings. In urban conditions, one can negotiate the intensity and frequency of the disruption of public life and traffic, whereas in regional conditions the common term is disaster, although there were many situations where local urban flooding had disastrous consequences (casualties and property losses) as well. However, floods do not necessarily always need to be associated with disastrous consequences."
- economic aspects: "deals with the issues of financing the capital improvement, operation, and maintenance of flood protection schemes. Local stormwater drainage and flood protection is usually financed by local revenues, such as local taxation, service fee, or user charge fee, collected on the basis of land use, whereas the regional protection is mostly carried out through general taxation."
- institutional aspects: "deals with the role of governments in the process of decision making. In local conditions all major decisions are made by local governmental institutions and water-related companies, whereas in regional issues federal government and ministries take over the full responsibility. Increasing participation of non-governmental organisations is becoming noticeable as well."
- technical aspects "deals with the concepts and works usually applied in flood protection. In urban conditions, the "dual drainage" concept is most commonly applied, introducing the distinction between the stormwater drainage service and urban flood protection, whereas in area-wide conditions flood control measures are always regarded as a part of the regional or state-wide flood control schemes.

Flood impacts come from the combination of these multiple aspects, which have consequences for integrated policies and risk management frameworks (WWAP-UNESCO 2006). On one hand, institutional coordination and management mechanisms need to be strengthened via the promotion of national disaster prevention forums including stakeholders. On the other hand, risk management strategies should address the preparedness of societies to deal with floods, taking into account risk perception issues by individuals and communities, and by developing education and communication approaches.

Education, training and communication at all levels have a key role to play in several stages of flood risk management, from preparedness stages (e.g. management, planning), to emergency response measures (e.g. management and coordination of communication and public information) and rehabilitation measures (e.g. causality and damage assessments and reporting, claim processing, psychological assistance, reconstruction efforts). While this paper focuses mostly on education, training and communication of communities and the general public, some brief remarks will be included regarding technical and institutional levels.

STAKEHOLDER PARTICIPATION

Urban flood management approaches are likely to prove counter productive in the long-term if they fail to enhance the capacity of individuals and society to cope with floods (Szöllösi-Nagy and Zevenbergen 2005). Self-protective measurements by residents of flood-prone urban areas can be particularly effective and may reduce the monetary costs of floods by 80% in some regions (Grothmann and Reusswig 2006). Moreover, active stakeholder participation implies the recognition that disaster preparedness is a joint responsibility of public authorities and the people. On one hand, it is virtually impossible for authorities to take efficient action against flood risks without public involvement and cooperation, in terms of self-protective measures and compliance with emergency instructions. It is also important for authorities to have a clear perspective on public perceptions, capacities and expectations. Thus, a key challenge on flood damage research consists integrating the social dynamics of flood risk perception, preparedness and vulnerability, in flood damage analysis and flood risk management (Messner and Meyer 2006). On the other hand, the public needs active support from authorities, among other issues to receive warnings about imminent floods, to receive information and coordination on the measures to be taken before, during and after flood events, and to promote learning on self-protective measures.

Several benefits of involving stakeholders in disaster risk reduction have been identified and include the following (Affeltranger, 2002; adapted from WWAP-UNESCO 2006):

- Before the disaster:
    - Improved hazard assessment by relying on local knowledge
    - Improved vulnerability analysis by identifying risk perceptions and hidden weaknesses
    - Assessment of self-protective capacity (awareness, knowledge and resources)
    - Assessment of information needs
    - Improved social understanding and ownership of official mitigation strategies
- During the disaster:
    - Helping capacity for relief in the neighborhood
    - Improved understanding of warnings and instructions
    - Improved trust in authorities and relief officials
- After the disaster:
    - Enhanced commitment to reconstruction activities

RISK PERCEPTION OF FLOODS

Risk perception influences flood risk preparedness and protective responses (e.g. Grothmann and Reusswig 2006; Miceli, Sotgiu and Settanni, 2008). Grothmann and Reusswig (2006) developed a model to explain protective responses to floods (damage prevention) based on protection motivation theory. This model hypothesizes that protection motivation is directly influenced by threat appraisal (perceived probability, perceived severity, combined with fear of floods) and coping appraisal (protective response efficacy, perceived self-efficacy, protective response costs), negatively mediated by non-protective responses (fatalism, denial, wishful thinking). The model also hypothesizes that protection motivation is directly influenced by threat experience appraisal and inversely influenced by reliance on public flood protection. Action towards protective responses is conditioned by actual barriers. The model was tested in Cologne, Germany. With particular relevance for this paper Grothmann and Reusswig (2006), found those with more information options of self-protection were also more likely to 1) take avoidance measures (i.e. avoidance of expensive furnishings in the basement and first floor); 2) purchase of flood protection devices (e.g. protective barriers for windows and doors or pumps); and 3) take structural measures (e.g., putting the heating in upper floors). Information was directly related with home ownership and with previous flood exposure and inversely related with non-protective responses and with reliance on public flood protection. Seeking of information on flood protection was considered itself a self-protection behaviour and was regarded by respondents as very easy, not costly and very effective.

Terpstra et al (2006) found that risk perception of floods in the Netherlands could be largely (74% of variance) explained by eight factors: global increase of flood risk, predictability and no dread, no dread and does not affect me, (un)known risk, risk benefit trade off, people exposed, (un)controllable situation and public commitment. On average, flood risks scored as slightly predictable and slightly known (i.e. very slightly above the mean point of the measurement scale). Interestingly, respondents tended to slightly agree that people like them know well the flood risks in the region and that they can estimate the chances of flooding. However they disagree that the risks of floods are well known to experts. Respondents also slightly agreed that the media often exaggerates the risk of floods and that authorities inform them well.

Research in Taiwan compared the perceptions of those that previously suffered from floods with the general public who have never no flood experience (Lin, Shaw and Ho, 2008). Victims have higher perceived risks of floods, and know more about mitigation actions but perceive less control over flood risks than non-victims. Victims tend to pay more attention to flood information than non-victims but at the same time tend to agree less with government plans to alert the public about a flood hazard. There are no significant differences between victims and non-victims regarding trust in the government’s capacity for crisis management, trust in experts’ capacity to issue flood warnings and trust in the media’s reports on flood warnings. Mitigation intentions were found to be inversely associated with powerlessness feelings.

Research in Japan found low levels of acceptability towards flood risks (Zhai and Ikeda 2008). Among other issues, the authors found flood risk acceptability inversely influenced with flood risk perception, budget information on structural flood measures and on preparedness for flood risks. Flood risk perception was strongly associated with the perception of other risks (e.g. natural disasters, urban risks, diseases) and with the perceived consequences of floods, but only weakly associated with the perception of flood probabilities.

COMMUNICATION OF FLOOD RISKS

The timely issuance of forecasting information and warnings, together with appropriate communication during preparedness phases, flooding episodes, mobilization, evacuation and post-crisis processes are key elements of flood emergencies management. Given the urgency associated with many urban flooding events, it is crucial that standard procedures are clearly established and functional. Research has identified sets of procedures for efficient flood information and communication. Such procedures focus, among other aspects, on the communicator, the communication channel and the message content. Overall, it is important to prepare in advance message maps for flood communication, based on a series of steps that include the identification of stakeholders and of their concerns, the development of key messages and preparation of supporting information (Lin and Petersen 2007).

With regards to the communicator, it is suggested that authorities should establish one main communication centre and designate one single experienced spokesperson for the mass-media. Such “one voice approach” is key to avoid needless misunderstandings due to inconsistent and conflicting messages, associated with the different tasks performed during flood management, that often lead to public confusion and anger. One key factor that is often highlighted in risk communication literature is trust. In order to ensure that people pay attention to the message and that the message is regarded as credible, it is crucial that the communicator is regarded as trustworthy. A series of factors influence trust, including perceptions of care, value similarity, competence, performance, integrity, cooperation, commitment, fairness, consistency, independence, and openness (e.g. Poortinga and Pidgeon, 2003). The ‘one mass-media spokesperson’ approach can be complemented at the local level by community leaders that have access to the main message adapted to the local circumstances and can help to disseminate it for instance in clubs, schools, churches, cooperatives and other public venues (e.g. Martens, Garrelts, Grunenberg, and Lange 2009). Involving local group leaders in flood management can enhance perceived local ownership of planning and relieve efforts.

The communications channels to be used – usually a combination of mass-media and interpersonal channels – should be clearly identified and communication routes should be pre-established to ensure timely communication within the short time available during flood events. These channels can vary according to the community and flood management stage. They usually comprise television, radio, websites, newspapers, leaflets, loudspeakers, emergency professionals, and community leaders. Two-way communication systems are often more reliable than one-way systems (Carter 1980). It is important to highlight that while interpersonal sources (e.g. family members and friends) are often overlooked, their influence on perceptions and behaviour related to water issues seems to be often stronger than that of mass-mediated sources (Doria, 2010). Parker and Handmer (1998) note that much of the flood-related information may be gathered from interpersonal sources and that the scope for personal networks to relay warnings and to contribute local knowledge towards system design appears to be large. In fact, Clifford (1956) noted that those who are warned through personal channels are more likely to believe in the message and to respond. In the United States, where flash floods are the most significant natural hazard and where half of related fatalities are of individuals in vehicles, it was found that barricades and signs often fail to deter motorists from crossing flooded areas (Coles et al. 2009). Most respondents to their survey have driven through a flooded roadway and the most influential factor for their decision is peer behavior, via the prior successful crossing of other vehicles.

With regards to the message content, it can vary largely depending on the stage, uncertainty and potential risks involved. At early stages, it may be simply a forecast of potential risks. While floods can often be forecasted in order to issue warnings for institutions and communities to prepare their response to flood risks, some difficult decisions must be made to issue warnings, as potential for issuing a false warning or retaining a legitimate warning can be high. False alarms may raise skepticism and future inaction (Cola 1996), but the risks involved in failing to issue warnings can be much higher.

The effective issuance of forecasting and warning notices requires a set of human and institutional capacities in place, as well as an enabling framework environment. In the particular case of urban flash floods, these tend to have a higher level of uncertain associated and are more difficult to forecast than tipical rural floods. Such particularly complex cases are likely to cause greater stress and reveal the strengths and weaknesses of the existing flood preparedness and response systems. A strongly coordinated system is needed for the timely preparation and efficient dissemination of forecasts and warnings.

An example of a forecasting and warning system, as provided by Andjelkovic (2001), is composed of six organizational sub-systems:

- Forecasting and warning centre: responsible for collection, evaluation and issuing of warning messages, responsible for monitoring the development of a flood threat and for offering advice and assistance to local emergency organisation; also responsible for training of institutional staff.

- Main emergency centre: coordinate and conduct emergency procedures during flood events.
- Community/local emergency organizations: responsible for specific activities in local areas, such as door-to-door warnings, search and rescue, evacuation of residents, moving valuables, clearing debris, registration and welfare of victims, co-ordination with: police, fire-fighters, medical and ambulance services, local utility companies.
- Other organizations: which may provide assistance and help before, during and after flooding events (e.g. United Nations Organizations, Red Cross, churches, schools, universities, charity organizations, non-governmental organizations).
- Mass media: helps in disseminating information and promoting communication.
- General public: take protective measures at the household and community levels to protect lives and property, may act upon warnings, may follow guidance for evacuation and relocation.

As events develop, more substantial messages are needed. Risk communication templates can be used to guide the preparation of messages to be issued during flood emergencies.

While a frequent recommendation is to keep the message simple, research has found that sufficient detail is needed for the message to be understood and accepted as credible and helpful (e.g. Carter 1980). Lave and Lave (1991) noted that government publications tended to omit relevant specific information on the nature and magnitude of flood risks and on what specific actions individuals can do to protect lives and property. Grothmann and Reusswig (2006) highlighted the importance of communicating not only what actions can be done to mitigate flood risks, but also the effectiveness and costs associated with private precautionary measures. Technical details (e.g. affected areas, time of occurrence, flow rates, duration of peak flows) should be included, along with basic practical issues. These include, for instance, information regarding the status of safety of driking water supply and in case it is disrupted, information about how people can access drinking water (Doria, Pidgeon, Haynes 2006). The development of GIS tools has strong potential in terms of model and mapping development than can be used to support communication. However, risk mapping literacy should not be taken for granted and must be piloted (Haynes et al. 2005).

In practice, there are several challenges associated with warning systems, including technical constraints (e.g. lack of data, modelling inadequacy and differing flood types), organizational constraints (e.g. weak dissemination of information and institutional deficiencies in the coordination of joint measures for risk management and disaster prevention) and social and cultural limitations (e.g. poor understanding of warnings, limited ownership, conflicting information sources and resistance to follow guidance and instructions) (WWAP-UNESCO. 2006). Social and cultural limitations can to some extent be adressed by user-based design approaches of warning systems, which enhance the warning interpretation, improve ownership and may decrease resistance to guidance and instructions. Therefore, it is crucial to involve stakeholders in the preparation and design of the warning and communication system (Affeltranger, 2002; McDaniels et al., 1999).

EDUCATION

Education is essential for effective disaster risk reduction. It contributes to save lives, prevent injuries and property damage, and helps to develop resilient communities that are able to minimize the economic, social, and cultural impacts of disasters (UNESCO 2010a). Moreover, research has found that formal education is sometimes linked with risk perception of flooding and the adoption of protective behaviours among the general public (e.g. Lave and Lave 1991). In this sense it is important to link early warning systems to education processes, so that there is clear communication between the authorities involved in both realms and so that learners and teachers receive up-to-date information.

The importance of education lies in preparedness, response and recovery, i.e. before, during and after a disaster has occurred. Even after a disaster strikes, education provision provides important life-saving and life-sustaining information. Education can provide physical protection, and strengthen the cognitive and psychosocial coping skills of learners. It can protect children and youth from exploitation and harm, which they are more vulnerable to following a disaster. It can be instrumental in disseminating vital information, for example, concerning safe drinking water; and it can provide a sense of normalcy, stability, structure and hope for the future in emergency situations. A valuable resource for policy makers and practitioners in education in emergencies is the Inter-Agency Network for Education in Emergency's (INEE) Minimum Standards for Education: Preparedness, response, recovery (Nicolai and Triplehorn, 2003).

An efficient response to flood hazards requires adequate education and training at all levels. At the technical and higher levels, education is needed for those directly specialized in flood risk management. This concerns a variety of technical disciplines, such as hydraulics, hydrology, meteorology, engineering, geology, geographic systems, economics, and psychology, among others. Anecdotic evidence at the global level suggests that the number of adequately trained professionals involved in risk management is far from enough to meet the challenges, particularly in developing countries. It is recognized that global changes, including urbanization and floods, imply an urgent need for highly qualified professionals in water and education (UNW-DPC, UNESCO, BMU 2009). Unfortunately, the scarcity of professionals in these areas only becomes evident during disasters. As a consequence, investments in this area often tend to fall short of the needs unless catastrophic flood events take place.

It should be noted that most of the key decisions affecting water issues are made outside of the water sector, by people with little or no education in water (WWAP-UNESCO. 2009). Public knowledge about flood processes is sometimes reported as scarce (e.g. Lave and Lave 1991, King 2000). Formal education can only influence the adoption of protective measures by individuals if flood-related education is adequately integrated into formal, informal and non-formal education. In areas where access to formal education is limited, which is often the case for those most vulnerable to disaster risks, authorities may help to ensure that messages are shared with non-formal education; there are clear links and opportunities to work with ‘public information’ and communication schemes on this account. Moreover, when developing flood management plans, authorities and flood experts should not assume that the general public has any specific knowledge about an event that may be relatively rare at the local level (i.e. in the case of the ‘100 year floods’), about which they had virtually no opportunities to learn about. It is therefore crucial that such learning opportunities are provided, particularly in flood-prone regions, via education and training programmes.

Education is also essential at the primary, secondary and community levels for all stakeholders in a life-long learning perspective. Adequate education in these contexts requires capacities of teachers, educators and media professionals to promote learning about floods. This implies knowledge across a variety of topics, materials and an enabling environment. While teachers are often likely to be well prepared in disciplinary terms (e.g. to teach geographic aspects of floods), knowledge on practical aspects (e.g. how a rescue system works) and the enabling environment (e.g. curriculum integration and professional development opportunities on flood-related issues) may need support (Chang, Chen and Chen, 2010). It should also be noted that serious flood events may seriously disrupt education systems and teachers should also be prepared to respond to floods. (e.g. Machtinger 2006/07). Education systems should also be prepared through the development of contingency plans. In what concerns the physical aspect of education facilities, is important to ensure that schools are not built on flood plains, or areas susceptible to floods and that education authorities have the professional support to determine whether an education facility is safe for use after a flood.

The provision of information and warnings is a distinct process from flood education. However, there are several links that should be considered. On one hand, literacy and related skills are valuable to correctly read and/or understand flood warnings and to interpret flood related information. One the other hand, the provision of flood risk warnings and information to intuitions and communities is futile if people do not have the knowledge and skills needed to respond adequately. In fact, lack of response capacity may only trigger frustration or inadequate responses that may further enhance risks during floods. Moreover, during flood disasters it may be impossible to provide timely information and instructions. This may happen for instance in the case of communities that became isolated and which will need to rely on their own capacities (King 2000). This is also often the case during particularly fast events such as flash floods (Siudak 1999).

Similarly to the development of communication strategies, flood education should be systematically developed and take into account public perception and stakeholders perspectives (e.g. Becker et al 2008).

In that regard, the DRR school programme following the floods in Namibia is an example of education project in floods that not only integrated disaster risk management knowledge in the school curricula, but also in the relevant training and learning programmes for stakeholders including development planners, emergency managers and local government officials (UNESCO 2010b).

CONCLUSIONS

The impact of floods is result of the interaction of several natural and human factors. Water-related risk education and communication are essential to strength the human response to floods. Education at all levels and communication have a key role in different stages of flood risk management, including preparedness, emergency responses and recovery.

This paper highlighted the importance of establishing clear and functional procedures for risk communication. Concerning education, it was noted that a holistic approach at all levels of education is necessary to strengthen public understanding and skills to cope with flood risks. Among other issues, this implies that teachers are capacitated to provide adequate learning opportunities in such complex multidisciplinary topic. In both communication and education processes, risk perception issues must be taken into consideration.

The role of non-structural measures such as education and communication remains under-researched and is often overlooked in formal flood risk management processes. However, human capacities and vulnerability have a central role in flood events and there is some evidence that they can lead to a very significant reduction of flood impacts, both in terms of human lives and property. In this context, education and communication certainly deserve higher attention and priority from those directly and indirectly involved in flood risk management.

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URBAN DRAINAGE TRENDS – A PATHWAY TOWARDS MORE SUSTAINABLE SOLUTIONS
TENDENCIAS DE DRENAJE URBANO – UN CAMINO HACIA SOLUCIONES MÁS SOSTENIBLES

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Abstract

Urbanization is certainly one of the man made actions that most influences flood aggravation and generates higher environmental impacts. Land use and population growth are critical issues for great cities, which suffer from floods, in a spiral cycle where they are also agents for worsening floods, due to vegetation removal, imperviousness and flow retentions reduction. Traditional practices of urban drainage design focus on end-of-pipe solutions, in order to adapt the network to the generated flows. Urban flooding is still often treated as a direct result of excessive rain, without regard on the basin behavior as an interrelated and interdependent system. The traditional approach for drainage system design is being supplemented or replaced by systemic solutions, with distributed actions over the basin. This concept has been gaining importance in recent years, configuring an integrated approach and launching the basis for a sustainable urban drainage system design. The diversity related to the urban flooding process makes this phenomenon difficult to assess. The interaction between the drainage system and the urban landscape structures produces complex flow patterns. In this situation, mathematical models may become an important tool in assisting the design of integrated flood control projects. A case study developed in Rio de Janeiro State and supported by a hydrodynamic flow cell model, called MODCEL, illustrates this discussion.

Keywords: Urban Floods, Sustainable Urban Drainage, Mathematical Modeling, MODCEL

Resumen

La urbanización es sin duda una de las acciones del hombre que más ha influido en la agravación de las inundaciones, generando así mayores impactos ambientales. El uso de la tierra y el crecimiento poblacional son temas críticos para las grandes ciudades víctimas de inundaciones, en un espiral donde ellas también son agentes que empeoran las inundaciones debido a la eliminación de vegetación, la impermeabilidad y la reducción de las retenciones de flujos. Las prácticas tradicionales de diseño de drenaje urbano se centran en soluciones de final de tubería, con el fin de adaptar la red a los flujos generados. Las inundaciones urbanas siguen siendo tratadas a menudo como un resultado directo del exceso de lluvias, sin tener en cuenta el comportamiento de las cuencas en tanto sistema interrelacionado e interdependiente. El enfoque tradicional para el diseño del sistema de drenaje está siendo complementado o sustituido por soluciones sistémicas con acciones distribuidas a lo largo de la cuenca. Este concepto ha ido ganando importancia en los últimos años, configurando un enfoque integrado e inaugurando la base para el diseño de un sistema sostenible de drenaje urbano. La diversidad asociada al proceso de las inundaciones urbanas hace que este sea un fenómeno difícil de evaluar. La interacción entre el sistema de drenaje y las estructuras del paisaje urbano produce patrones de flujo complejos. Ante esta situación, los modelos matemáticos pueden convertirse en una herramienta importante para contribuir a la elaboración de proyectos integrados para el control de inundaciones. Un estudio de caso desarrollado en el Estado de Río de Janeiro y apoyado por un modelo hidrodinámico de simulación de cuencas, llamado MODCEL, ilustra esta discusión.

Palabras clave: Inundaciones urbanas, Drenaje urbano sostenible, Modelo matemático, MODCEL

1. INTRODUCTION

Water is essential to life and the cities depend on this resource to develop. Ancient cities grew near watercourses and the rivers, in particular, were responsible for water supply, soil fertilization after floods, irrigation, waste conveyance, fluvial transportation and defense against invaders. The development of cities along time, especially after the Industrial Revolution, suffered a great acceleration and the consequences for the industrial cities led to several infrastructure problems, diseases and environmental degradation.

Nowadays, several cities of developed countries tend to integrate and valorize rivers as a natural resource and part of the urban landscape, trying to join natural and built environments. In developing countries, however, rivers usually suffer urban and social pressures, with irregular occupation of their banks, acting as conveyors of waste waters and presenting a degraded environmental situation. Late and fast industrialization is not always accomplished with appropriate urban infrastructure. Most times, these cities turn their back to the rivers.

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Urbanization is certainly one of the man made processes that most influence the aggravation of floods, especially from the consequences related to changes in land use. This is one of the major problems in growing cities in present times. Therefore, the cities suffer from floods, in a spiral cycle in which they are also agents of floodsworsening. It is very difficult to discuss urban flood control, in a sustainable way, without discussing the city itself, the land use and the urban development.

Statistics show that floods are the natural phenomenon that causes most damage and losses throughout the world. According to Freeman (1999), 60% of human life losses and 30% of economic losses caused by natural disasters are due to floods. Clarke and King (2004) show a map of disasters, related to floods, showing deaths and losses per continent. The numbers are impressive. In Asia, between 1992 and 2001, there were 50.034 deaths and losses of 105 billions of dollars. In America, there were 35.848 deaths and 31 billions of dollars in losses. In Europe, 32 billion dollars of losses were computed, with 1362 deaths. The number of great inundations is increasing exponentially along past centuries. According to a publication of the World Bank, (Jha et al., 2012), 178 million people were affected by floods in the year of 2010 and the total losses exceeded 40 billion dollars, in the same year. This increasing trend follows what is also happening with the world population and, more specifically, with the urban population. The built environment leads to the concentration of people and goods, increasing exposition and vulnerability, whilst helping to worsen floods. More and more people are becoming affected by flood events.

Flaws in urban drainage systems lead to the flooding of large areas. This situation interferes with the functioning of the entire city, affecting sanitation, housing, transport, public health, among others systems. This is an issue with technical, socio-economical, institutional and environmental connotations. The understanding of how urbanization affects the flooding process is a very important issue for proper planning and designing of urban drainage systems and flood control measures (when necessary). The urbanization of a watershed tends to promote the removal of the original vegetation cover, to occupy the riverine areas and the flood plains, and to increase imperviousness. Thus, larger volumes of water become available to flow more quickly and accumulate in low areas, often already occupied. When urbanization is not adequately planned nor controlled, more severe consequences appear. The cities grow and establish themselves as poles of attraction, receiving a migrant population, with illusions of a better life quality, but several times this population ends up in peripheral, impoverished and critical areas, conforming slums without infrastructure and sanitation. Figure 1, for example, shows a critical situation on Acari River Basin, in Rio de Janeiro city.

Figure 1: Scene from AcariRiver Basin, in Rio de Janeiro, Brazil. (Font: CityMunicipality – Rio-Águas, 2007)

Therefore, several challenges are faced by the urban drainage systems nowadays: population growth and fast urban development; uncontrolled land use and occupation; environmental degradation; excess of imperviousness and heat islands formation, due to local influence of urbanization, interfering with intense rainfall and increasing basin discharges; possible climate changes in a relative near future, increasing extreme rainfall events and the mean sea level. These problems need to be addressed adequately and technical solutions must evolve to face them. Engineering, Architecture, Urbanism, Environmental and Social Sciences must be considered in a multidisciplinary approach in order to meet sustainable standards for the urban development, integrating efforts towards practical solutions.

2. BRIEF HISTORY OF THE CITIES AND URBAN DRAINAGE EVOLUTION

It can be said that the main role as an agent of urbanization in ancient times was played by Rome. The Roman engineering stood out both in the context of buildings and monuments, as well as in fulfilling the needed infrastructure for a city to grow. Ferrari (1991) reports that in the fourth century AD Rome had more than 1 million inhabitants, 19 aqueducts able to supply the city with one million m³/day, sewerage system, paved streets, more than 45,000 buildings, some up to 8 floors, 80 palaces, and was protected by walls, in addition to a number of baths, theaters, amphitheaters, temples, and other monuments.

During the Roman era, significant advances were introduced in the design of urban drainage. Concerns about the urban flood mitigation and the need for lowlands drainage were very important to the city, settled on the riparian areas of the Tiber River, in a marsh region. To meet the needs of urban drainage, a complex network of open channels, landfills and underground pipes were built. This system was also used to transport sewerage from the housing areas (Burian and Edwards, 2002).

The fall of Rome led to the loss of importance of the cities and the urbanization process decayed during the Middle Ages. Europe has come to live in a state of almost permanent warfare. Concerns with sanitation deteriorated and the streets were used indiscriminately as the only means of disposal of wastewater and storm water runoff (Chocat et al., 2001).

The resumption of trade from the thirteenth century on was mainly a result of the recovery of the city importance. The Renaissance, on the fifteenth century, marks the movement to rescue knowledge of classical antiquity. Architecture and Urban Art converges to Urban Planning. At this time, also hydrology and hydraulics sciences began to develop faster.

Biswas (1970), in his book about the history of Hydrology, illustrates an interesting passage where Giovanni Fontana, studying the flood of the Tiber River in Rome, during Christmas 1598, pointed out several negative effects generated due to the lack of information from people who have settled their houses in marginal (and floodable) areas of the river and its tributaries. It is remarkable how this Fontana's observation could be repeated nowadays.

The Industrial Revolution marked a profound change in society, causing an increase in goods availability and services provision, associated with the effect of technical and economic transformations, increasing cities' attraction. In parallel, the Liberalism stimulated the reduction of public intervention in all sectors of social life, including urban controls, believing that the necessary adjustments would be provided by society. The consequences were critical to the cities - the urban growth occurred quickly and disorderly.

In this context, poor sanitation became a critical issue to urban life. Plagues easily spread bringing death in a large scale. Streets were used to convey both rainwater and wastewater. Urban floods began to increase in magnitude and frequency, what worsened sanitation problems, spreading contaminated waters over large areas. As a consequence, the role of urban drainage has become crucial in the life of cities. To face this problem, drainage systems were designed to fast convey and safely dispose storm waters. At this time, a hygienist phase took place in the drainage development, pointing directly towards improving flow conductance aiming to control water related diseases. This became the main objective of urban drainage systems until a few decades ago.

In developing countries, the late industrialization induced an even faster urban development and population growth, mainly on the second half of the twentieth century. Thus, the expected situation of buildings and structures designed properly, in a city governed by an urban development plan, referred only to a portion of the population. Another part had no formal access to the city services and had to organize on their own, in precarious and irregular conditions, with all the negative consequences of these agglomerations. Poverty and lack of infrastructure led to urban chaos. The formation of an irregular city near to the regular one has forced to reconsider the development of modern urbanism.

From the perspective of urban flood problems, considering this rapid urban growth over the last two centuries, it became difficult to simply propose drainage network corrections, such as canalizations, rectifications or pipe enlargement. Canalizations could not account for all urban flooding problems and, in fact, this approach tended to transfer problems to downstream areas, rather than to solve them. Engineering became aware that the existing infrastructure was being overloaded. Project solutions focused on the consequences of the urbanization process, that is, the runoff continuous increasing and this concept could not stand alone anymore. Increasing conveyance indefinitely was not the needed answer to this problem. Source control, acting on flood causes, using storage and infiltration measures, emerged as a new technical option in the 1970s (Andoh and Iwugo, 2002). An integrated approach, considering the river basin as the unit of work, became the basis for a sustainable urban drainage system design and several concepts were developed in this context, gaining importance along time.

3. URBAN DRAINAGE TRADITIONAL DESIGN

Traditional practices of urban drainage design are based on canalization works in order to adapt the system to receive and convey the new generated and concentrated runoff. This approach equates the undesirable consequences of the process, which are the greater and faster discharges produced by the built environment.

The urban drainage system comprises two main subsystems: micro-drainage and macro-drainage. Microdrainage is the system of conducts constructed for receiving and conveying the storm water that flows from the urban surfaces (building roofs, lots, streets, squares, etc). The micro-drainage system is essentially defined by the layout of the streets in urban areas. The macro-drainage, by its side, is intended to receive and provide the final discharge of the surface runoff taken by the micro-drainage net. Macrodrainage corresponds to the main drainage network, consisting of rivers and complementary works, such as artificial canals, storm water galleries, dikes and other constructed structures.

In general terms, the urban drainage system design comprises the following steps:

- Subdivision of the area into sub-basins.
- Design of the network integrating urban patterns and natural flow paths, trying to match with topographic conditions.
- Definition of the design rainfall, considering a time of recurrence, depending on the safety desired for the project, and a time of duration, associated with the concentration time of each sub-basin considered – calculation is made step by step, as the sub-basins are summed to compose greater areas;
- Determination of design discharges through the Rational Method, for example, or another hydrological method, if convenient.
- Hydraulic design of each drainage network reach, using Manning or Chèzy formulas, to conduct the maximum discharge found in the previous topic. Sometimes, in the macro-drainage context, the channel design considers a maximum discharge produced by the watershed that contributes to the stretch of canal that is being calculated. Then, with this flow, the channel is calculated through backwater formulas, considering steady varied flow. Figure 2 shows a schematic view of micro and macro-drainage calculation.

This approach greatly simplifies the real situation. In the design context, it may not be serious, once all the calculations follow a certain pre-defined order and the effects are accumulated. However, discharges in a drainage system are, in fact, unsteady. In a situa-

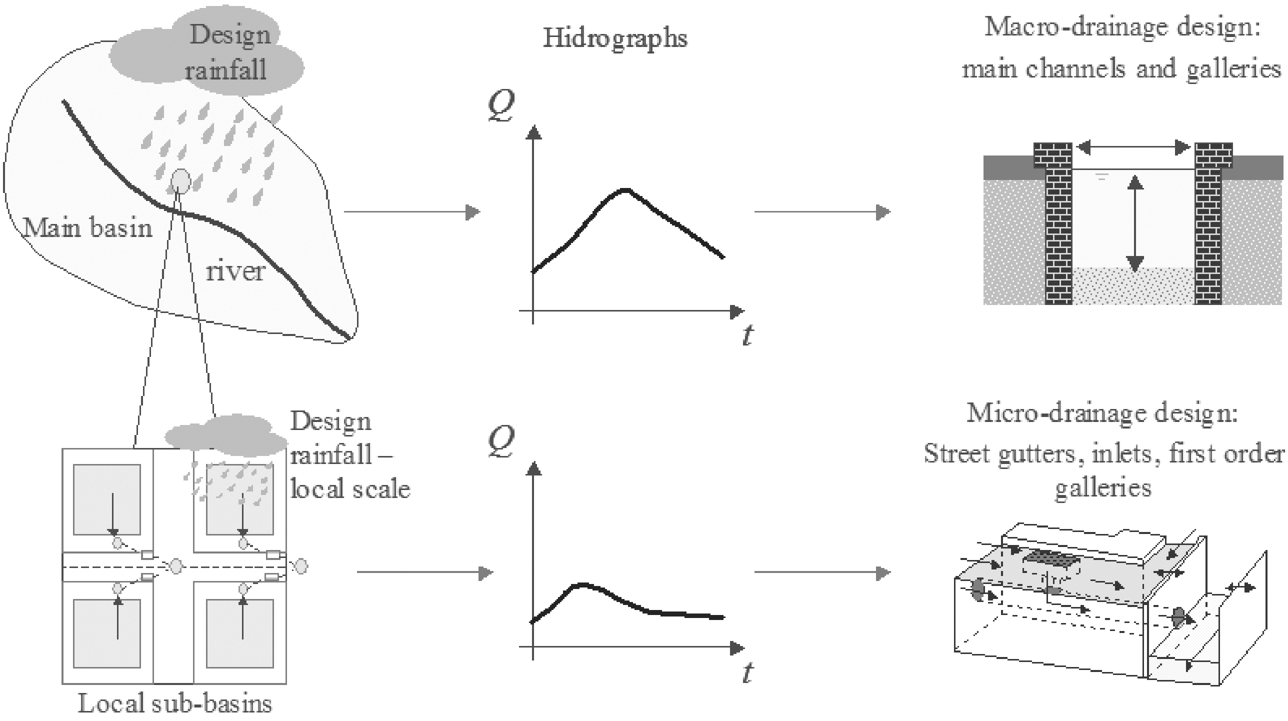

Figure 2: Schematic view of micro and macro-drainage calculation

tion of flood occurrence (drainage system failure), for example, with the project already implemented, it is not recommended to work in such a simplified form. Diagnosis is something that needs a systemic approach. The combination of effects in time and space becomes crucial for the assessment of flow conditions. Besides, closed conduits introduce an even more complex element, when the system fails. Under this condition, the design discharge is surpassed and flow under pressure may occur, replacing the basic hydraulic laws of free surface flow, which has guided the original project.

4. URBAN DRAINAGE DESIGN TRENDS

The traditional approach for drainage system design is being supplemented or replaced by newer concepts that seek for systemic solutions, with distributed actions over the basin, trying to recover flow patterns similar to those prior to urbanization. It is important to emphasize the necessity of systemic solutions, regarding the basin as the basic design reference.

These newer concepts, with little differences, highlight the necessity to reduce impacts over the urban water cycle, recovering (as close as possible) natural functions. Among these concepts, some are detached below as frequent references on urban flood control:

- Best Management Practices (BMP) –concept developed from the 1970’s, working on the runoff generation control, regarding aspects of quantity and quality (AMEC, 2001). In Brazil, a similar concept was formalized more recently, considering the introduction of compensatory techniques to account for urbanization effects over flow patterns and urban water cycle (Baptista et al. ,2005)
- Low impact Development (LID) -in the 1980s, this concept appeared as an alternative for the urban water management, trying to recover the natural characteristics of the water cycle. The LID concept proposes the use of techniques that may be able to increase the local capacity of interception, infiltration and evaporation of the rainwaters, also increasing the opportunities for storage and slow the runoff generated by urbanization, in order to make it as similar as possible to the natural behavior (Walsh and Pomeroy, 2012; Ahiablame et al. 2012).
- Sustainable Urban Drainage Systems (SUDS) – this concept integrates aspects of flood control and urban design. Drainage systems can be developed to improve urban design, managing environmental risks and enhancing built environment. SUDS objectives account both for reducing quantity and quality problems and maximizing amenities and biodiversity opportunities (CIRIA, 2007)
- Water Sensitive Urban Design (WSUDS): this concept may be defined as an interdisciplinary cooperation involving water management, urban design and landscape architecture, combining water management tools and urban design approach and facilitating synergiesfor the ecological, economic, social and cultural sustainability (Langenbach et al. , 2008). WSUDS is related with a framework of physical sciences, social–economic sciences, community values and legal and institutional aspects (Wong, 2006).

New urban subdivisions must consider the challenge of developing urban areas without changing natural hydrological patterns (Souza et al., 2005). Storage and infiltration measures are considered together in integrated design solutions (Souza et al., 2012). Moreover, these new trends add concerns of water quality control, as well as enhance rainwater as a resource to be exploited in an integrated approach for sustainable management of urban stormwaters.

Besides, the possibility of combining flood control measures with urban landscape interventions, capable to add value to urban spaces (figure 3), with multiple functions, is becoming an interesting option from the point of view of revitalizing degraded areas, as well as the optimization of available resources and public investments.

5. MATHEMATICAL MODELING TO SUPPORT THE SYSTEMIC APPROACH TRENDS AND NEEDS

The occurrence of floods, with channel overflowing and surcharging of storm galleries, makes urban landscape structures start to work in order to supplement the network that failed. Streets begin to act as channels and these flows may gain independent paths. Transpositions may occur from a sub-basin to another, changing the patterns expected on the original drainage system project. Overflowing discharges may pass through several drowned inlets until they find the chance to return to the network. Flooded squares and public spaces start to act as reservoirs, damping flows and also changing drainage patterns originally planned. This situation happens in an undesirable way, once houses may be flooded in this process and several losses may occur. Eventually, lack of maintenance of micro-drainage can cause flooding, with harmful consequences, even when macrodrainage still presents capacity of flow.

The diversity related to the urban flooding process makes this phenomenon difficult to assess. The possibilities of effect combinations in space and time are not trivial. The interaction between the drainage system and urban landscape structures, which eventually acquire hydraulic functions, in a complementary way, produces an unpredictable drainage network, distinct from the one that was originally designed. Flow patterns developed on this new complex sys-

Figure 3: Examples of multifunctional landscapes – a detention basin in Santiago–Chile and a retention basin in La Rochelle-France. (Font: authors' personal collection, 2009).

tem is not known in advance. Thus, it is not possible to simply accumulate effects or compose a step by step calculation. Local solutions can lead to undesirable effects, with the simple transfer of problems. Apparently good solutions for different places may combine negatively effects due to temporal composition of the hydrographs generated. Sometimes, different interventions just overlay concurrent results. On the other hand, it is possible to generate better results, with extra benefits, when proposing adequate combinations of measures capable to join efforts in the desired direction.

In this situation, mathematical models may be able to assist in the design of integrated flood control projects, because of the possibility of conducting a systematic evaluation of the basin. The observation of different project arrangements can be simulated in various scenarios of combined interventions and future development hypothesis.

Many models, with different characteristics, may be cited, in order to illustrate the discussion on how to treat flood problems. Among these models, some free options are the SWMM - Storm Water Management Model, developed by the United States Environmental Protection Agency (EPA), mainly used for storm drains design, and the Hydrologic Modeling System (HEC-HMS), developed by US Army Corps of Engineers (USACE), which focuses on rivers or major drainage design. Presently, there are several alternatives of 1D-2D modelling, which seem to be the most promising alternative in this field (Leandro et al., 2009, Simões et al., 2011, Castellarin et al., 2011). A quasi 2D model, developed in the Federal University of Rio de Janeiro (UFRJ), charcterized by being a free and academic model, is MODCEL, which will be briefly presented here and then used in a case study, with the aim of demonstrate how critical an uncontrolled urban development may be, and alsocomparing an urban drainage traditional design with new trends in urban flood projects.

MODCEL

MODCEL (Mascarenhas and Miguez, 2002) is a hydrodynamic model based on the concept of flow cells (Zanobetti et al., 1970), capable to represent the urban basin in an integrated way, by building a network of compartments covering the entire surface. Each cell performs a rainfall-runoff transformation process and the connections among cells compose a network responsible for representing flow patterns. The mass conservation principle is applied for all cells and hydraulic laws are written for all flow relations. The several hydraulic laws are taken in a one dimensional way, although the space modelling creates a pseudo 3D representation. Two layers of flow are vertically connected. The superficial layer that represents the surface of the basin, joining streets, squares and open channels, interacts with the layer that represents the network of underground galleries. Figure 4 shows a schematic view of MODCEL, in a real basin of Rio de Janeiro city.

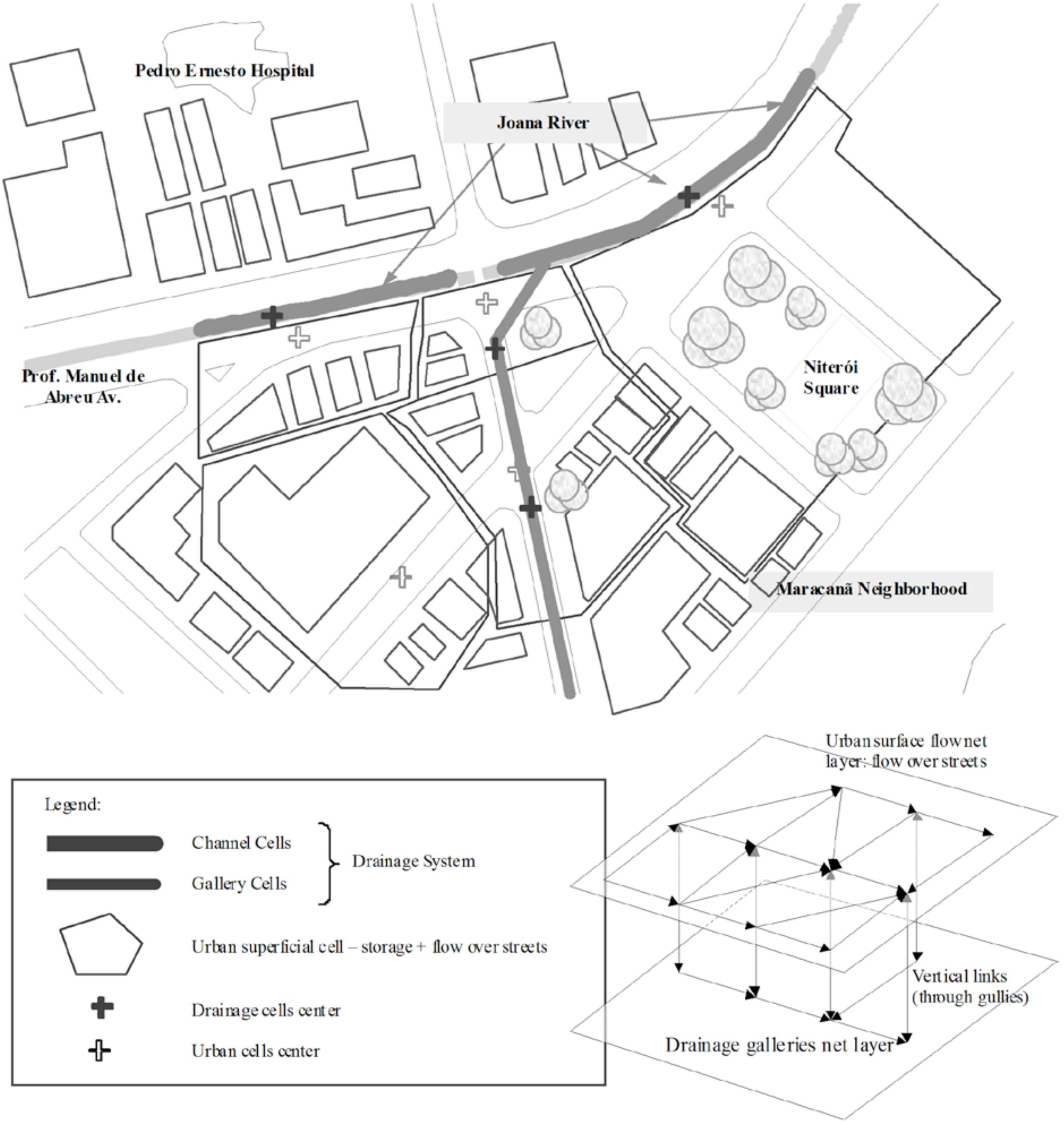

Figure 4: Schematic view of a MODCEL representation.

Case Study: Iguaçu-Sarapuí River Basins and the particular problem of Pilar-Calombé Rivers, at the Metropolitan Rio de Janeiro Region

A case study was developed for a heavily occupied and densely populated urban area, at the Metropolitan Region of Rio de Janeiro, in the Iguaçu-Sarapuí River Basin, located in the western portion of the Guanabara Bay. Figure 5 shows a map of this area, with the Cities that are inside this basin. This is one of the most critical areas in the state regarding urban flooding. The region presents great urban and industrial areas, as well as wide rural zones in an urbanizing process, and reminiscent areas of natural Atlantic Forest on the upstream reaches of the basin. This basin was included by the State Governmentin a Program of Environment Recuperation, and the Federal University of Rio de Janeiro was responsible for the flood control studies. The basin was modeled with MODCEL, in order to provide the basis for assessing present situation, prospecting future scenarios and proposing flooding control measures. There were very few measurements available for calibrating the model. In fact, there was one river gauge at Botas River, the main upper tributary of Iguaçu River. There was a set of four control points at Sarapuí River, associates to a previous hydrological Study and there were maximum levels registered for one single event on Iguaçu River. This set of information was combined to give a minimum support for calibration. At downstream, Guanabara Bay was represented by tide levels. Figure 6 shows the mapped flood conditions for present situation, represented over the modelled flooded area of Iguaçu River Basin. Figure 7 shows a future scenario considering that there will be no control on land use. Considering these situations, regarding present problems and the future perspective, a set of measures intending to control land use and recover storage capacities were proposed. In particular, several different areas were modelled in details, using the general model to provide the set of boundary information. One of these cutouts refers to the case study focused in the sequence and which is used to exemplify the differences between the two approaches discussed in this paper for flood control: the traditional one and the sustainable one.

The basin of the Pilar-Calombé Rivers, in the city of Duque de Caxias, at Rio de JaneiroState, in Brazil, suffers from floods, in a very low land, called Baixada Fluminense. This area is experiencing an important urban growth. The PilarRiver has approximately 11.3 km, and drains a basin with 10.8 km2 of surface area. The CalombéRiver has an approximate length of 9.3 km, draining an area of about of 15.0 km². The CalombéRiver is, in fact, a tributary of PilarRiver, arriving from its left margin. After the confluence, this basin flows to the IguaçuRiver, an important river of Rio de JaneiroState, mainly because of its localization in the metropolitan area and its outfall to Guanabara Bay.

MODCEL was used to construct a flooding map for the basin, considering a design rainfall of 20 years of recurrence time. Figure 8 shows the division of the basin in cells. The obtained flooding map can be seen in Figure 9.

In order to solve this problem, two approaches were developed in different design propositions. The first set of measures focused on the traditional approach, and the rivers conveyances were raised. Rivers were canalized in rectangular concrete sections, with sufficient capacity to avoid overbank flows. The second set of measures were based on urban waters sustainable management concepts and focused on:

Recovery of implemented flow sections, by cleaning local obstructions and redefining a trapezoidal section in natural soil;

Recovery of the vegetation in strategic areas of the basin, especially on hill slopes;

Recovery of natural flooding areas of the basin (riverine lowlands) and implementation of a floodplain river park along the right bank of Pilar River and at some parts of Calombé River, where urbanization is still not too dense;

Use of detention reservoirs in urban public squares.

After the simulation of the proposed scenarios, all flooded areas inside the basins of the Calombé and Pilar Rivers were mitigated, for both sets of measures. However, the traditional approach led to downstream flooding, where it did not happened before, as it can be seen in figure 10. Table 1 summarizes the discharge results for both scenarios, at the outfall of the basin. The concrete canalization approach almost doubled discharges to downstream reaches. The sustainable approach, however, solved the flooding problem without changing significantly downstream discharges.

CONCLUSIONS

The traditional end-of-pipe approach tends to transfer flooding problems downstream and require frequent investment to resize the channels in order to meet the needs of increasing runoff flows generated by the urban development. Cities are growing faster, especially in developing countries, and the urbanization is not always planned nor controlled. This is probably one of the main challenges that cities will face: rationalize land use and develop in a sustainable way. In this way, the sustainable management of urban rainwater provides a viable alternative to face the trends of urban floods aggravation. The recovery of hydrological functions and the reorganization of flow patterns in space and time may be the solution for urban flood control. In order to adequately assess the effects of a proposed set of measures, the aid of mathematical models may be very useful. The case study shown in this paper shows that it is possible to evaluate the present situation at the Calombé-Pilar River basin, to identify the problem of transferring floods downstream when canalizing the rivers, and to

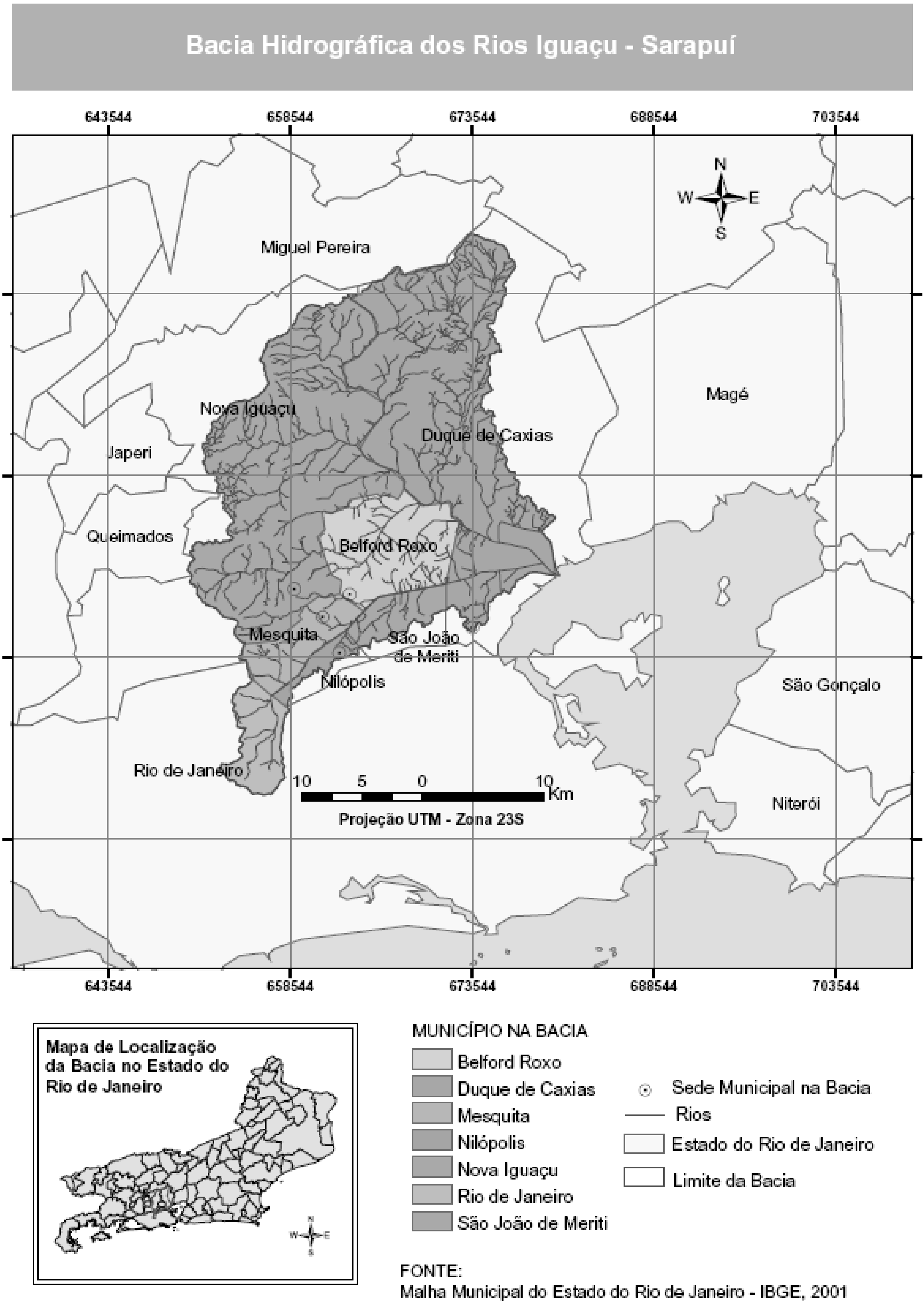

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Figure 5:Iguaçu-SarapuíRiver Basin at Baixada Fluminense Lowlands in the Metropolitan Area of Rio de Janeiro.

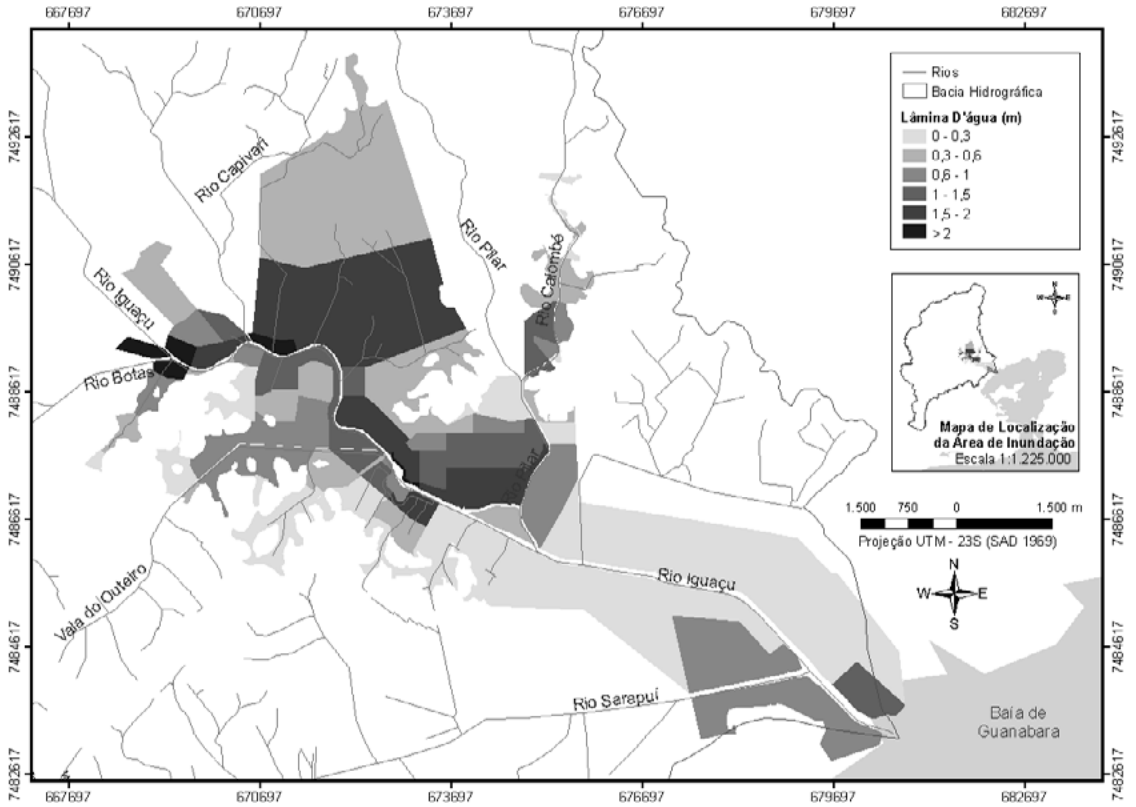

Figure 6: Flood map for Iguaçu River Basin, in the present situation, for a design rainfall of 20 years of return period, calculated with MODCEL

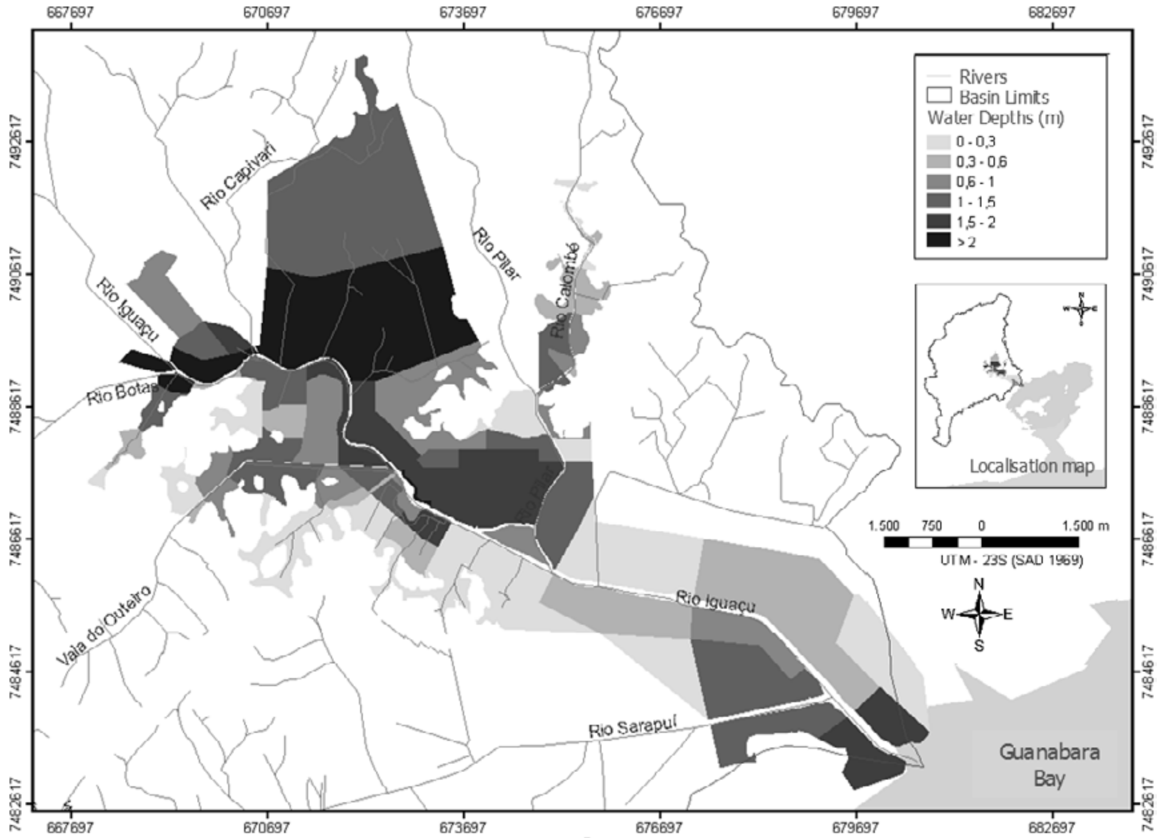

Figure 7: Flood map forIguaçuRiver Basin, in a future uncontrolled urban growth situation, for a design rainfall of 20 years of return period, calculated with MODCEL.

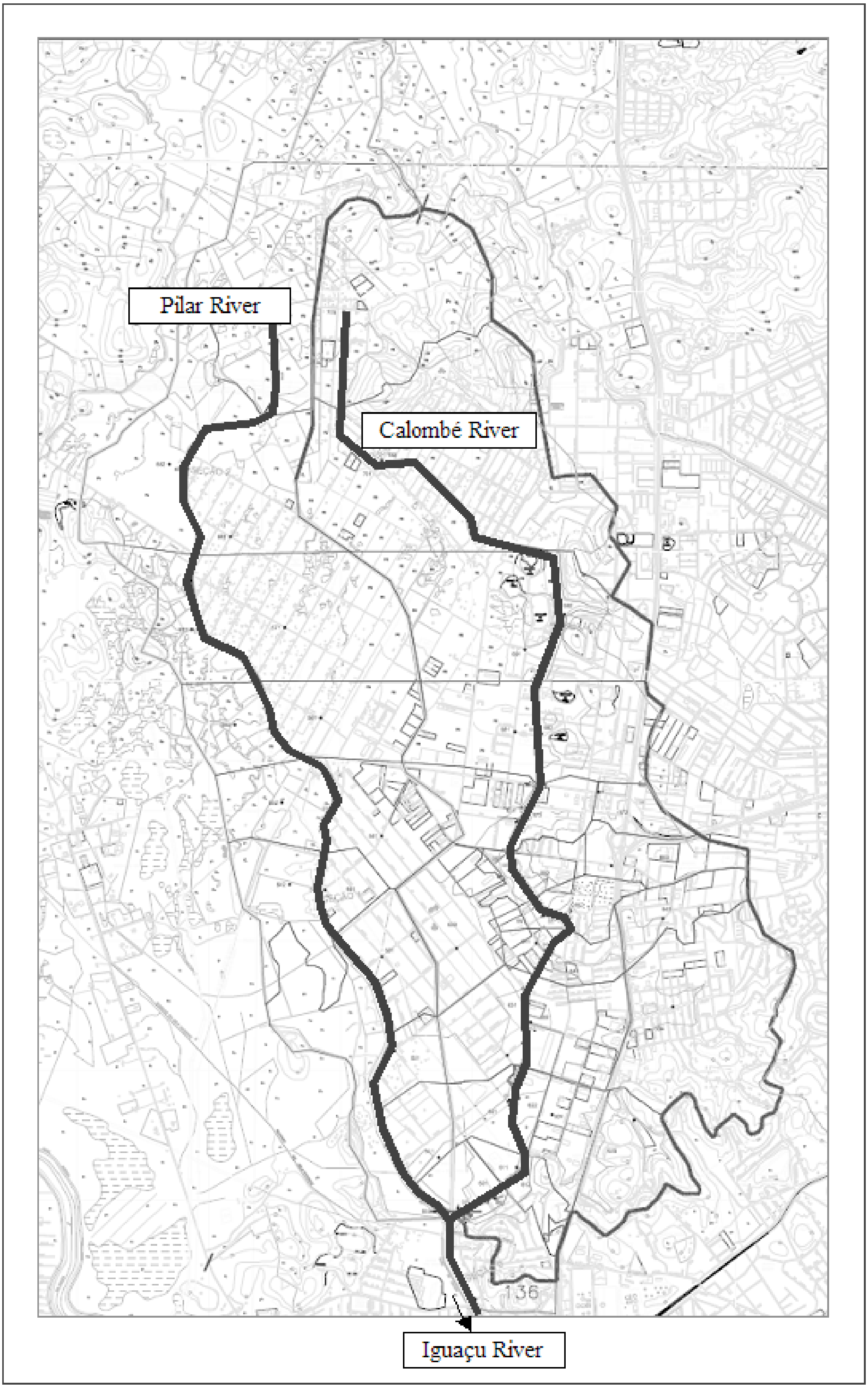

Figure 8: Cell division modeling for Pilar-CalombéRiver basin

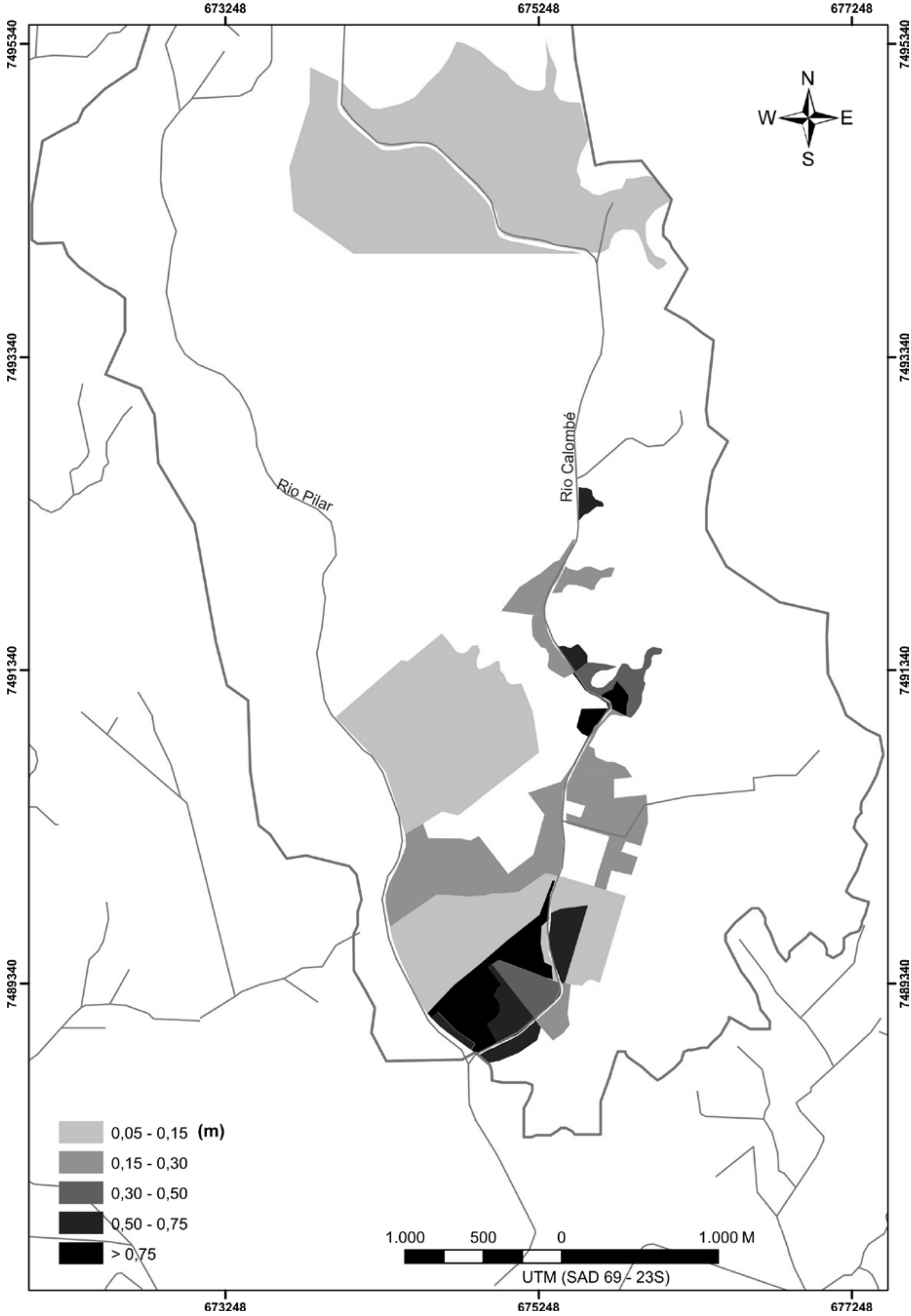

Figure 9: Flooding map for present situation – basin diagnosis

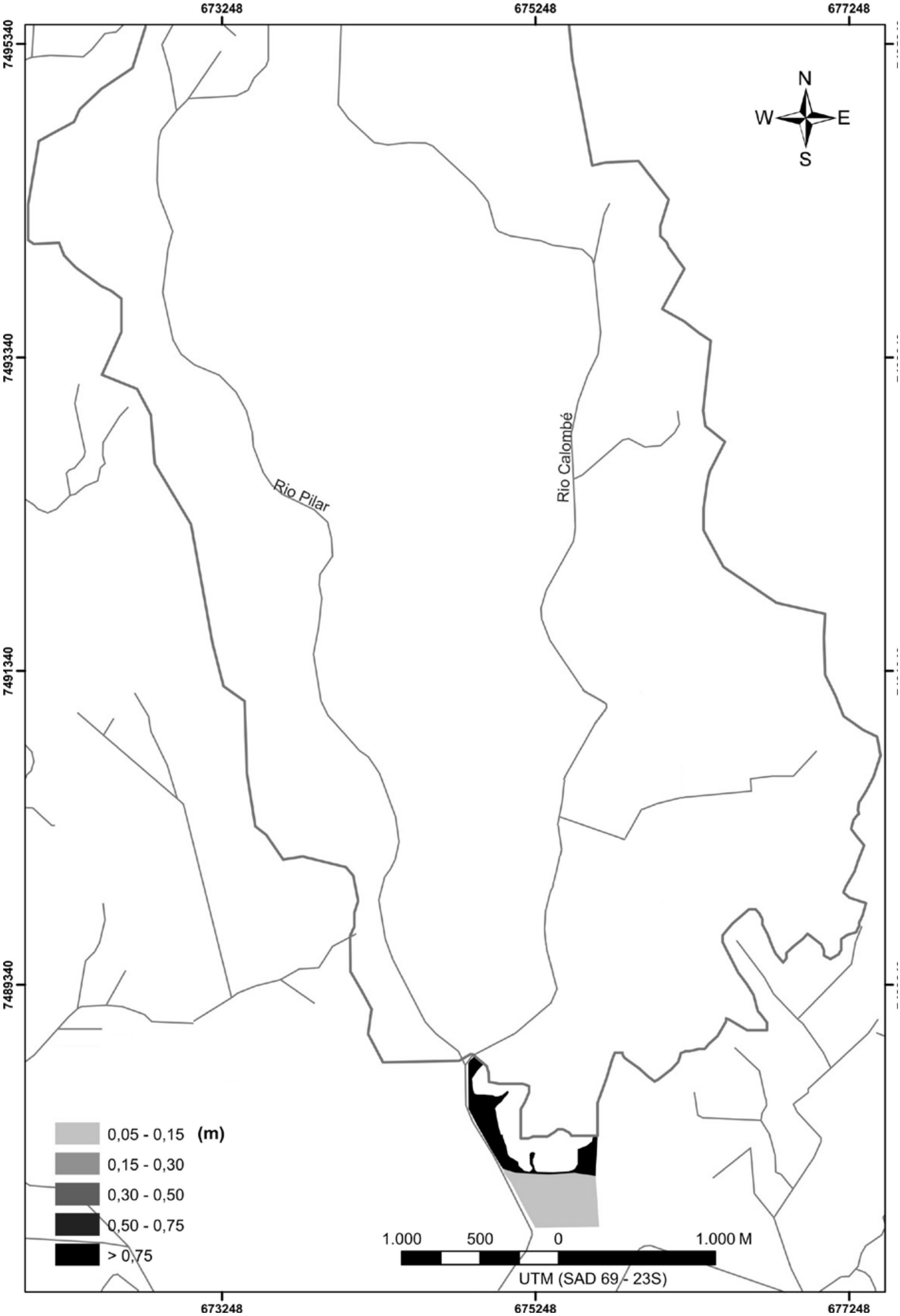

Figure 10: Flooding map for traditional canalization approach – flooding effects transferred downstream.

Tables:

Table 1: Discharges for Pilar-CalombéRiver basin outfall, considering different recurrence times.

TR (years)	Discharges on Macro-Drainage System Outfall		
	Present Situation	**Canalization**	**Sustainable Approach**
10	17,17 m^3/s	32,08 m^3/s	15,78 m^3/s
20	17,47 m^3/s	34,73 m^3/s	17,38 m^3/s
50	17,88 m^3/s	36,51 m^3/s	19,35 m^3/s

adequately simulate the distribution of storage measures over the basin, even outside the drainage net.

Urban flood solutions need to be discussed, planned and designed in an integrated way with the city itself, the land use control and the expected urban development.

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