MODELLING THE EFFECTS OF LONG-TERM URBAN LAND USE CHANGE ON THE WATER BALANCE

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Abstract
The level of land consumption for housing and transport contrasts sharply with both the necessity and the legal obligation to maintain the ecological potential afforded by open spaces to meet the needs of current and future generations in terms of resource protection and climate change. Owing to the increasing intensity of soil usage, in many urban landscapes the soil conditions has deteriorated. The natural filter and run-off regulating functions of soils are impaired or even disappeared altogether by land surfacing. Since such soil functions closely depend on the soil's biophysical properties, the decline of water balance functionality caused by urbanisation and increasing imperviousness varies. In response to the demand to sustainably secure urban water resources, it needs to be assessed exactly how land surfacing affects the functions concerned. Analysing and evaluating the urban land use change and the respective imperviousness on the long-term water balance ought to improve our general understanding of the water household related impact of urbanisation. Therefore, the aim of this paper is to assess the impact of urban land use change and land surfacing on the long-term water balance over a 130-year trajectory using the example of Leipzig. In particular, attention is to be paid to evapotranspiration, direct runoff and groundwater recharge.

Keywords: Water balance; Imperviousness; ABIMO; Messer model; Land use change; Leipzig

1. Introduction

Within the last decades extensive urbanisation and land consumption processes have become an increasingly prominent though contentious theme in both public and academic discussions on land use change (Antrop, 2004). Although impervious land worldwide makes up a percentage of 0.43% of the total land area (Elvidge et al. 2007), in many European countries we find >10% of urbanised and commercial land (Nuissl et al. 2007). Forward-looking studies imply that these dynamics will not abate (Antrop, 2004; Kasanko et al. 2006). To the most important modifications that affect the urban water balance belongs the increase of the impervious cover (Grimm et al. 2008).

There are numerous case studies on spatio-temporal and functional effects of urbanisation on ecosystems (Breuste, 1996). These studies demonstrated that urban land consumption affects the environment in terms of, biodiversity (e.g. Löfvenhaft et al. 2002), habitat suitability (e.g. Hirzel et al. 2002), microclimate (e.g. Pauleit et al. 2005), or photosynthesis, water balance and water regulation (e.g. Interlandi and Crockett, 2003) (e.g. Imhoff et al. 2000). But looking at a more long-term impact requires a comparison of different time slots. There are only very few studies which provide empirical evidence to what extent urbanisation processes from the beginning of the industrialisation onwards impacted the natural environment in form of landscape functions (Haase and Nuissl, 2007; Haase et al. 2007).

The objective of the paper is to study the impact of urbanisation on the long-term urban water balance. Based on a long-term trajectory of land use change over a period of more than a century, from 1870 to 2003, and it presents a case study for the city of Leipzig. The analysis focuses on effects for mean annual evapotranspiration, precipitation, direct runoff and groundwater recharge rate.

2. Study Area

The studied town Leipzig in Germany was founded in the 11^{th} century, and it has a long history as an important urban centre and currently has around half a million inhabitants. Situated in the eastern part of Germany, the former German Democratic Republic, it experienced little urban sprawl in the post-World War II period until 1989. Already before, Leipzig underwent a period of vibrant growth between 1870 and 1930, reaching its historical maximum with a population of more than 700,000 in the early 1930s, which then made it Germany's fourth-largest city. After 1989, post-socialist transformation again ushered in a period of heavy urban sprawl, with several shopping malls, commercial parks and residential neighbourhoods spreading, in this order of time, into the city's suburban periphery. Industrial decline, low birth rates and out-migration, however, contradicted the expectations linked to these investments and led to a surplus of housing, office space and developed land. Since the late 1990s urban sprawl around Leipzig has abated considerably. Following the incorporation of several suburban townships in recent years, the administrative territory of Leipzig today covers almost 30,000 ha (297.5 sq. km) and has a population of around 505,000 (Haase and Nuissl, 2007).

Leipzig suits well as a case study for modelling the effects of long-term land use change on the water balance since it has been facing simultaneous processes of societal and economic transition and demographic change. This makes the case of Leipzig a fairly typical one for the development of large cities in the former socialist Europe. As many old industrialised cities in the West have to deal with similar problems, Leipzig is also a general example of the medium-sized city that has ceased growing in the developed world (Banzhaf et al. 2007). Leipzig is of a highly diverse land use structure which let expect differentiated results of an impact assessment of urbanisation. Apart from the inner city, which consists of a solid, dense structure of 19th and 20th century Wilhelminian-style[1] housing blocks, the city's territory contains large areas of the typically suburban mixture of land uses, including agricultural land and floodplain forests (Haase and Nuissl, 2007).

3. Methods and Materials

3.1. Detecting land use and cover change

Monitoring long-term land use change in the study area resorted to different data sources: Firstly, topographic maps and the digital land use information system for Germany (ATKIS) from 1870, 1940, 1985, 1997, and 2003. Moreover planning maps and documents for areas dedicated to future land use change, were used to create a digital land use data base. Secondly, field surveys were carried out in order to obtain the missing (detailed) information on land use in particular areas. From these sources, GIS-based vector files containing land-use nomenclature and derived sealing rates were established. Thirdly, existing studies on the historic and current development of Leipzig and its region were analysed so as to comprehend the respective framework conditions of land conversion (Haase et al. 2007).

Based on methodological findings by Steinhardt and Volk (2002) and Frede et al. (2002) and drawing on reference data from other studies on Leipzig (Wickop et al. 1998; Münchow, 1999) as well as field experiments, it was possible to assign a percentage of average impervious cover to each of the urban land use classes identified at a scale of 1:25,000 (Table 1). Along with Münchow (1999), a set of urban land use types, characterised in terms of built-up form, use, surfacing and drainage, could be discerned. When different information concerning the degree of surfacing in a particular structural type was found, the mean value was used. Thus, a scale-specific and -spanning classification of impervious cover (see Tables 1 and 2) for the entire study region was obtained, providing the data base for both water balance models ABIMO and Messer (cf. Fig. 1 in section 2.3).

3.1. Water balance model

Deal and Schunk (2004) argue that surfacing open land, especially in connection with the compaction and improvement of the soil-born drainage network, results in higher and accelerated direct runoff flows which turn to be critical since they provoke firstly a drop in groundwater recharge rates and subsequently also in the low-water flow of receiving water. Secondly, a reduction in water content in the urban atmosphere, and thirdly, a decline in the water retention and filtering capacity of soils and surfaces for pollutants (Collin and Melloul, 2003; Emmerling and Udelhoven, 2002). Fourthly, in case of heavy rainfall events the sewer systems

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[1] Wilhelminian-style means that the buildings were built starting after the German-French war which ended 1871 until 1910-18.

and wastewater treatment plants are assumed to be not capable of collecting the total amount of direct runoff resulting in an increased flood risk.

Table 1. Classification of imperviousness and canalisation for different field-scale classified urban land use types as required input data for the ABIMO model (Haase & Nuissl, 2007)

Land use type	**Aggregated land use class (Figure 2)**	**Degree of imperviousness (%)**	**Canalisation (%)**
Old rural settlement core	Housing before 1940	65	80
Multi-storey row houses (60ies)	Prefabricated houses	40	50
Prefabricated multi-storey houses	Prefabricated houses	60	15
Residential single house park (90ies)	Single houses	70	85
Single houses	Single houses	50	36
Wilhelminian style tenement houses	Housing before 1940	80	85
Villas	Housing before 1940	50	50
City Centre	Housing before 1940	95	60
Commercial area	Commerce	90	95
Trade area	Commerce	85	85
Service Sector	Commerce	85	75
Hospitals	Commerce	40	66
Education	Commerce	75	66
Military ground	Commerce	55	75
Water supply, waste water treatment	Commerce	50	90
Roads	Transport	30	20
Railway	Railway	85	90
Sports ground	Parks, allotments	40	20
Park	Parks, allotments	20	20
Allotment	Parks, allotments	20	20
Cemetery	Parks, allotments	15	20

To assess the effects of a long-term land use change on such functionalities the water balance model ABIMO (Glugla and Fürtig, 1997; Fig. 1) was applied to quantify the major variables of the long-term water balance for a city, for the time period from 1870-2003.

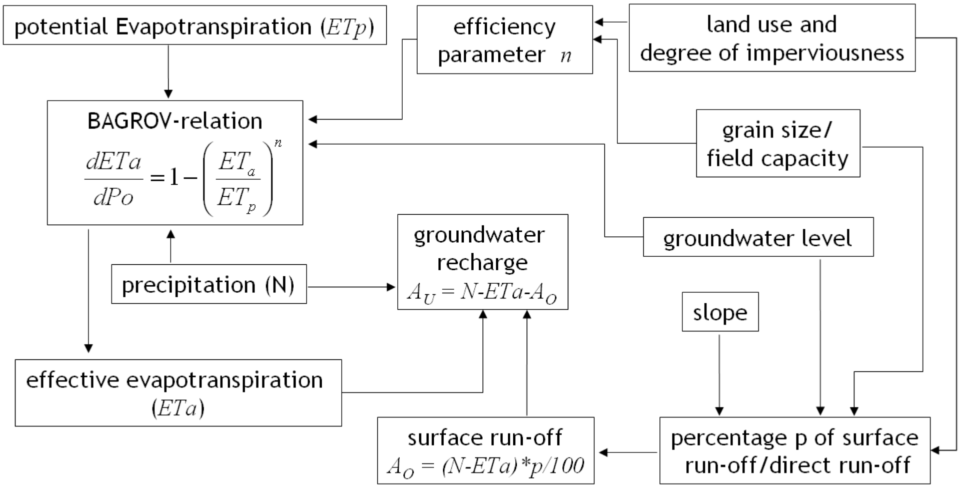

Figure 1. Logic of the ABIMO (vertical water flows: precipitation, evapotranspiration, groundwater recharge) and Messer (horizontal water flow: direct run-off) models to calculate the urban water balance (Glugla & Fürtig, 1991; Messer, 1997)

ABIMO was designed by the German Federal Institute of Hydrology for modelling the water balance in the quaternary area of Central Germany (pleistocene and holocene sediments and substrates with vertical seeping behaviour of the soils) and later modified for urban areas. ABIMO determines the base flow A_u of an area from the mean actual evapotranspiration ET_a and the long-term mean precipitation rate P_o. ABIMO uses the BAGROV-relation to determine the actual evapotranspiration ETa of an area (Eqs. 1–2):

$$R = P_o - ET_a \tag{1}$$

$$\frac{dET_a}{dP_o} = 1 - \left(\frac{ET_a}{ET_p}\right)^n \tag{2}$$

The BAGROV-relation is based on the evaluation of long-term percolation field studies. It describes the non-linear relation between precipitation and evaporation in dependence on soil grain size, field capacity, land use and respective drainage properties. With knowledge of precipitation rate P_o, and potential evaporation ET_p, and the efficiency parameter n, the BAGROV relation determines the real evaporation R for areas without groundwater influence (used as proxy for vertical flow without lateral influence; Haase and Nuissl, 2007). With increasing precipitation P_o, real evaporation R approaches potential evaporation ET_p, or the quotient R/ET_p approaches a value of 1. With decreasing precipitation P_o, real evaporation R approaches precipitation P_o. The efficiency parameter n covers the modification of the water storage capacity of the evaporative zone due to land use, degree of imperviousness and soil properties of each site (Glugla & Fürtig, 1997). The function of the drainage and sewer system is estimated according to the land use classes and included in the ABIMO model via the parameter degree of canalisation (%; cf. Table 2).

A second model to calculate the water direct runoff in urban areas was developed by adapting a runoff-model by Schroeder and Wyrwich (1990) to the conditions in the highly urbanised Ruhr-area in Germany (Messer, 1997). Based on the ABIMO base flow data, Messer's model calculates direct runoff rates in an area from the soil slope gradient, the soil type, its grain size, the ground water level (the deeper the water table, the lower the direct runoff), land use, and the degree of imperviousness (cf. Fig. 1). The direct runoff A_o equals the proportion p of excess water (difference between precipitation and evapotranspiration; Eq. 3):

$$A_o = \frac{(P_o - ET_a) \cdot p}{100} \tag{3}$$

The factor p is much higher in the case of cohesive soils (silt, clay) compared to non-cohesive ones (sand). Concerning land use p decreases in the order of farmland, grassland and forest. In the case of surfaced areas, p rises with the degree of imperviousness (Messer, 1997; Table 2).

Table 2. Proportion p of base flow A_u (modified according to Messer, 1997).

Slope	0–2%					
Grain size	Sand			Loam		
Groundwater table depth	<1 m	1–2 m	>2 m	<1 m	1–2 m	>2 m
Land use and imperviousness						
Farmland/grassland	50	0	0	50	20	20
Mixed woodland	20	0	0	30	5	0
Surfacing 1–20%	38	8	8	42	20	20
Surfacing 21–40%	58	43	28	61	51	42
Surfacing 41–60%	73	62	52	74	67	60
Surfacing 61–80%	86	79	73	86	82	79
Surfacing 81–100%	92	89	87	92	91	90
Water	0	0	0	0	0	0

4. Results

4.1. Urbanisation and land surfacing

In 1870, the city of Leipzig had largely preserved its mediaeval shape and huge parts of the current city (89%) were covered by arable land and forest (Fig. 2). Contrary to the assumption among local and regional representatives of nature conservation, the size of forest area in Leipzig (~ 20 km^2) has not changed much since 1870 (~10% = 30 km^2). On the other hand, the decrease of alluvial and riparian wetlands and grassland has been considerable (-6.8 km^2). Leipzig's development into a compact industrial city between 1870 and 1940 was accompanied by the embankment and canalisation of the rivers, causing the floodplains in the inner city to almost entirely disappear. Concurrently, large allotment sites (14 km^2) emerged and on the former outskirts, the number of detached and semi-detached houses increased considerably in the 1920s and 1930s (cf. again Fig. 2).

During the socialist period (1945-1989) ongoing urban land mainly occurred along the transport axes. Apart from the further decrease in arable and open land due to this moderate strip development, land use change also occurred due to reconstruction work in the inner city areas, where vacant lots and brownfields resulting from the devastations of World War II were partially redeveloped. The most striking change in land use in this period was the establishment of an enormous housing estate for 100,000 inhabitants on the city's western fringe between 1976-1989. Other, though much smaller, housing estates were built on Leipzig's periphery (Fig. 2). Processes of urban sprawl after the German reunification 1990 meant a further decrease in the proportion of arable and open land (-45%). In total, land use change in the 1990s brought about an increase in surfaced land of about 10 km^2 (x %) (Couch et al. 2005; Nuissl and Rink, 2005).

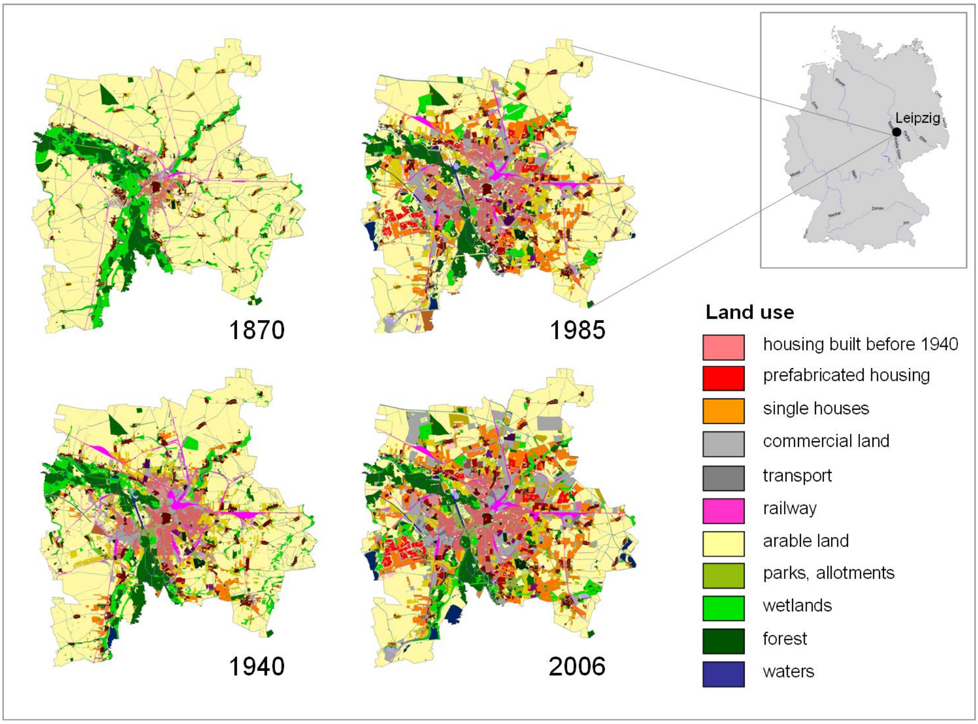

Figure 2. Land use change in the city between 1870 and 2006 (using the recent administrative boundaries of Leipzig). We find a first phase of growth after 1870 representing the industrialisation and transport development until World War II. Although Leipzig is up to present a compact city particularly after the German reunification in 1990 we can prove a kind of urban sprawl into the rural hinterland which is connected with land surfacing and an add on of impervious land. First and foremost the north-eastern part of the city underwent a dramatic increase of built-up land after 1990.

Between 1945 and 2003, the surfaced areas in Leipzig increased by 48.7 km² (19%). In both absolute and proportional terms, Leipzig has more impervious land compared to other Eastern Central European cities of similar size, such as Dresden (Germany), Brno (Czech Republic), or Bratislava (Slovak Republic; Urban Audit, 2008). The reason for this can be found in the traditional compact and densely built urban structures which largely survived World War II. Whereas, during socialist times, mainly new industrial and large housing estates contributed to land surfacing, today the largest share of newly surfaced areas is accounted for by residential land with a medium proportion of impervious land (>40–60%, see Table 1). Highly surfaced areas (>80–100%), such as industrial and commercial land, also account for a large part of the land newly developed after 1990. Compared to that, areas with a limited proportion of impervious surface (>0–20%) such as public parks and gardens but also private allotments, make up for about 18% of land urbanised since 1940 (Fig. 3; Haase and Nuissl, 2007; Banzhaf et al. 2007).

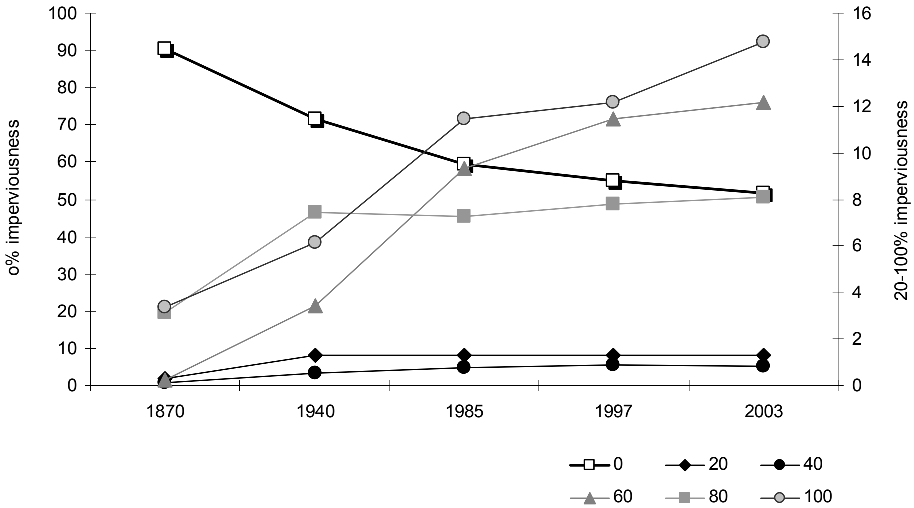

Figure 3. Development of the degree of imperviousness in Leipzig from 1870 to 2003. Whereas the proportion of none or low impervious land dramatically decreases particularly the classes representing high degrees of imperviousness – 60-100% – increase from 1940 onwards.

3.2. Water balance change

In the study area, un-surfaced land mainly features direct runoff rates of about 25–l50 mm, as the loess soils here usually have high field capacities and are therefore able to take up and store notable quantities of precipitation water. Due to land surfacing after 1870, particularly after 1990, the study area's high overall run-off control functionality has been decreasing severely (Fig. 4). In areas with a limited amount of impervious land the amount of direct run-off is increasing: the runoff control starts to deteriorate as of a share of impervious land of >20% where the direct runoff values start to double. Where the degree of imperviousness amounts to >40–60%, respectively, direct run-off increases by as much as 200 mm/a (e.g. in prefabricated housing estates). Once the share of impervious land exceeds 60%, runoff control drops by >200 mm/a and wherever it is >80%, run-off control drops by more than 300 mm (Fig. 4).

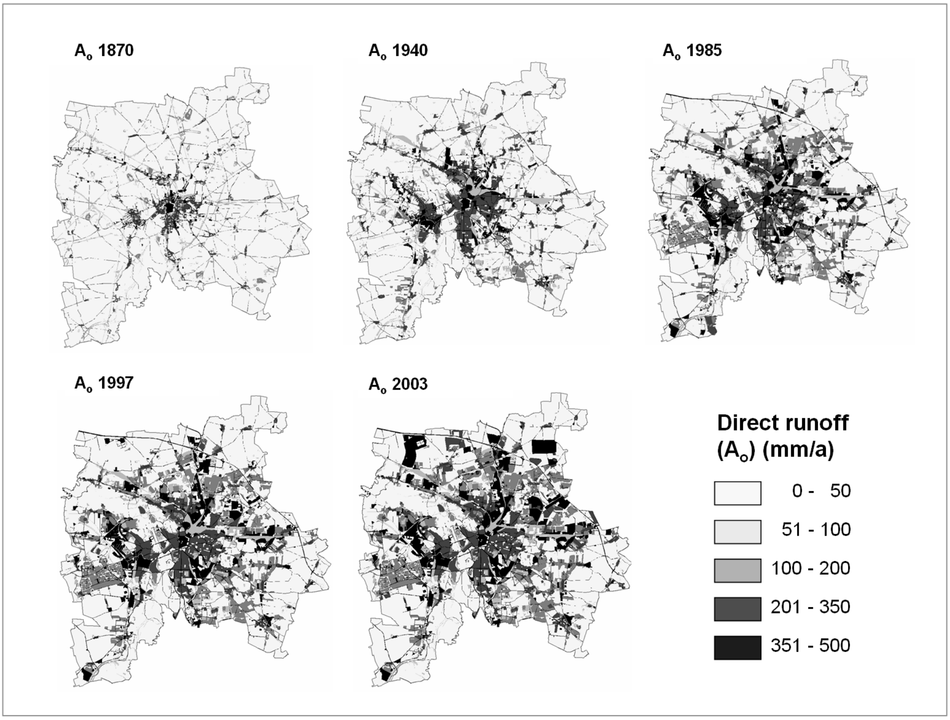

Figure 4. Change of mean annual direct runoff rates (A_o) 1870-2003

With an average annual precipitation of 560–580mm (mean value for 1961–90), an increase in direct run-off of up to 450 mm/a (which is >200% of the total annual precipitation) has been modelled in those areas that have been almost entirely surfaced (>80–100%) in the northern part of the city mostly in form of commercial land, the new airport and transport ways. These highest sealed surfaces we find particularly for commercial land and residential parks built after 1990. The smaller the amount of impervious surface in newly developed areas, the more moderate the increase in direct run-off is, as there remains enough bare soil in which the precipitation water could percolate and infiltrate (Fig. 4 and 6). Direct run-off also increases less severely where the soil had a poor infiltration capacity before it was surfaced. This holds in particular for loamy soils.

The increase in direct run-off is above all accompanied by a decline in actual evapotranspiration rates. In areas with a share of impervious land of >20–40%, evapotranspiration declines by 100–150 mm/a; in areas where this share is very high (>80–100%), it goes down by as much as 450 mm/a. Overall, this means that the water regime is shifting towards direct run-off throughout the study area (Fig. 5).

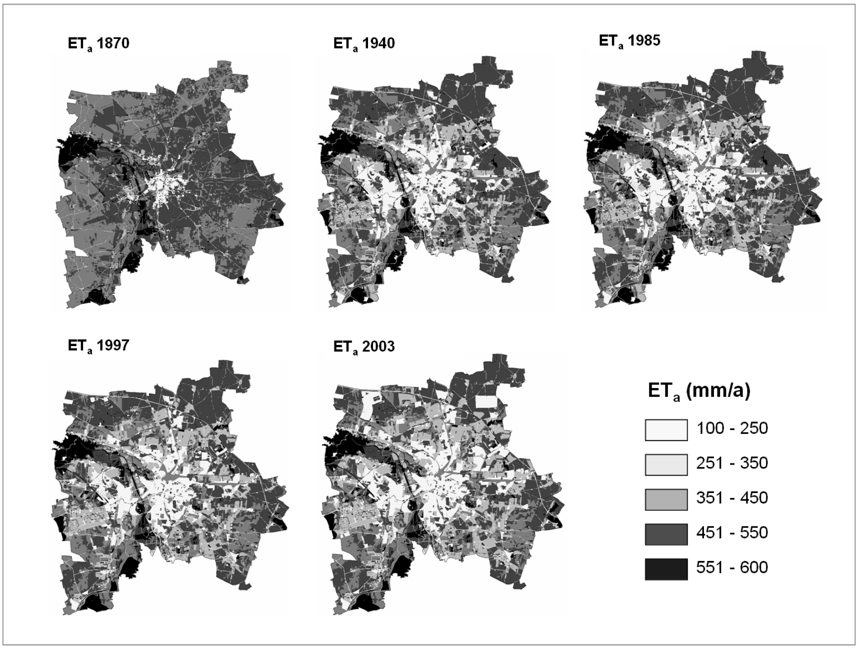

Figure 5. Change of mean annual evapotranspiration rates (ET_a) 1870-2003.

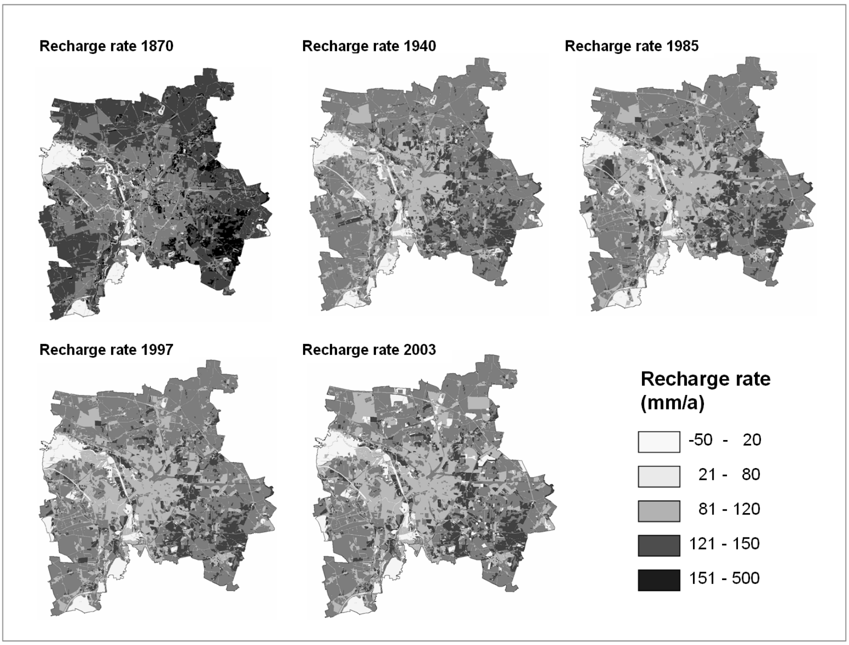

Figure 6. Change of mean annual groundwater recharge rates 1870-2003.

Due to changes in land use, the groundwater recharge rates on agricultural land are about 125–175mm from East to West of the study region, which is in line with the distribution of precipitation. The amount of percolation in areas where surfacing is up to 60% could be as much as 100 mm/a. In areas where surfacing is >60%, percolation has declined by up to 150 mm/a (Fig. 6).

Looking at the overall changes of the urban water balance caused by urbanisation and land surfacing we find a considerable decrease of evapotranspiration fluxes up to 25% (compared to 1870 which serves a baseline). Compared to that, the direct runoff rates dramatically increased from 1870 onwards to 282% in 2003 (Table 3).

Table 3. Changes of the long-term water balance (proportions of ET_a, A_o and A_u) in Leipzig taking the earliest time step from 1870 as 100%

Year	Evapotranspiration (ET_a)	Direct runoff (A_o)	Groundwater recharge (A_u)
		%	
1870	100	100	100
1940	90	174	103
1985	81	196	105
2003	75	282	96
Δ 1870-2003	**-25**	**182**	**-4**

The groundwater recharge rate only slightly decreases so that we can conclude that the water cycling in Leipzig accelerates through urbanisation. The water holding capacity drops in favour of an increasing direct runoff. This demands the subterranean canalisation network as well as the waste water treatment.

3.2. Parameter sensitivity of input data for ABIMO model outputs

In order to test the parameter sensitivity of ABIMO and in doing so determine uncertainties of the here presented modelling approach a number of simulations have been carried out using a range of different input values for the most decisive model parameters such as the degree of imperviousness, real evapotranspiration (represented by the effectiveness parameter n) and soil field capacity. For most of these parameters it is difficult to determine "the one" valid value of a model cell since they are all derived from, partially analogue, soil, land use or hydrological GIS data using rule-based assignment procedures. Here miss-assignments or misinterpretation of the basic (analogue or field) data could occur in the way that imperviousness and canalisation are over- or underestimated for specific land use types or that soil gain size is hard to determine for heterogeneous urban substrates.

Table 5 shows that the model output concerning evapotranspiration and base flow differ depending on the degree of canalisation and imperviousness that are assigned to open parks and green land uses in the ABIMO model. The highest values for ET_a and thus the most "natural" water balance the model produces when the degree of canalisation is low and the degree of imperviousness low to medium (n ~1.5; Table 4). On the contrary, the lowest output values for evapotranspiration are produced when the degree of canalisation is above 0 although the degree of imperviousness with <40% is lower than in the case shown in the middle of Table 5 where the degree of imperviousness is <60%. As the share of single house area and urban green increased since 1870 the range of ET_a increases from 106mm in 1870 to 150mm in 1997 and 2003.

Table 4. Ranges of model output values for Evapotranspiration (ET_a) and Base Flow (A_u) for single house areas and urban green spaces using different classification procedures in ABIMO: the degree of canalisation (C) differs from 0-20% and the degree of impervious between <20-<60% (determining the actual evapotranspiration ET_a represented by the effectiveness parameter n).

Evapotranspiration ET_a [mm/a]

	Simulation A*	Simulation B	Simulation C	Δ ET$_a$
1870	431-505	353-440	403-477	42-148
1940	427-507	351-507	401-507	0-148
1985	427-503	351-503	401-503	0-148
1997	427-505	351-503	401-503	0-150
2003	427-507	351-504	401-504	0-150

Base flow A_u [mm/a]

	Simulation A	Simulation B	Simulation C	Δ A$_u$
1870	92-192	132-261	185-274	59-185
1940	78-196	78-276	138-288	51-158
1985	78-194	78-268	138-281	51-158
1997	78-194	78-271	138-283	51-159
2003	78-195	78-271	138-283	51-159

*Sim. A: C = 0%; I = <40% / Sim. B: C = 0%; I = <60% / Sim. C: C = 20%: I = <20%

Another range of simulations were carried out looking at the sensitivity of the groundwater level, the soil grain size and the soil field capacity as model input parameters (Table 5). The results of this uncertainty analysis show that in case of high groundwater levels (<1m) as model input the models result concerning the output variable ET_a do not differ largely (500-504 mm/a). Compared to this, the base flow (A_u) differs considerably between 78-127 mm/a. Changes of the soil field capacity as model input parameter do not influence the ABIMO outputs, particularly when the groundwater table is close to the surface. With increasing soil field capacity the uncertainties of the ET_a output variables decrease – the more water is stored in the soils the more can be delivered for the latent ET_a flow.

Table 5. Ranges of Evapotranspiration (ET_a) and Base Flow (A_u) calculated for single house areas and urban green spaces using different classification procedures in ABIMO: the degree of canalisation (C) differs from 0-20% and the degree of impervious between <20-<60% (determining the actual evapotranspiration ET_a represented by the effectiveness parameter n). Groundwater levels and soil field capacities for different grain sizes had been modified, too.

Range of Evapotranspiration ET_a [mm/a] at a groundwater level of 1-2 meters

FC*	N [mm/a]	Sim.** A	Sim.** B	Sim.** C	Δ A-B	Δ A-C	Δ C-B
14 (T♦)	541-585	500-504	352-369	402-417	135-150	87-100	48-50
15 (L)	541-593	500-507	359-379	408-426	128-143	81-94	47-49
17 (L+U)	531-579	500-504	372-391	418-435	113-129	69-83	44-46
18 (S)	538-584	500-505	387-406	432-449	99-113	56-68	43-54
21 (L)	531-569	500-503	415-430	459-469	70-86	31-42	39-44

Range of Base Flow A_u [mm/a] at a groundwater level of 1-2 meters

FC	N [mm/a]	Sim.** A	Sim.** B	Sim.** C	Δ A-B	Δ A-C	Δ C-B
14 (T)	541-585	88-133	237-269	247-281	136-149	148-159	10-12
15 (L)	541-593	88-139	231-267	241-208	128-143	141-153	10-13
17 (L+U)	531-579	78-127	207-240	221-257	113-129	130-143	14-17
18 (S)	538-584	86-132	200-231	214-248	99-114	116-128	14-17
21 (L)	531-569	78-120	164-190	180-211	70-86	91-102	16-21

Range of Evapotranspiration ET_a [mm/a] at a groundwater level of >2 m

FC	N [mm/a]	Sim.** A	Sim.** B	Sim.** C	Δ A-B	Δ A-C	Δ C-B
14 (T)	538-586	430-450	351-369	401-417	79-81	29-33	48-50
15 (L)	533-596	429-455	356-308	406-427	73-75	23-28	47-50
15.5 (L)	538-591	430-451	365-385	414-431	65-66	16-20	46-49
17 (L+U)	531-592	428-452	372-396	419-439	55-57	9-14	42-47
18 (S)	538-592	461-483	387-408	432-451	73-75	28-32	42-46
21 (L)	531-592	458-481	416-440	460-476	41-43	0-6	36-44
22 (U)	539-580	461-480	422-441	464-479	39	1-3	38-42
25 (U)	537-578	459-460	429-443	468-174	30-31	8-9	39

Range of Base Flow A_u [mm/a] at a groundwater level of >2 m

FC	N [mm/a]	Sim.** A	Sim.** B	Sim.** C	Δ A-B	Δ A-C	Δ C-B
14 (T)	538-586	56-190	236-271	246-283	79-81	89-93	10-12
15 (L)	533-596	152-195	225-269	235-282	73-74	83-87	10-13
15.5 (L)	538-591	156-193	221-259	233-273	65-66	77-80	12-14
17 (L+U)	531-592	151-194	206-250	220-286	55-57	69-74	14-18
18 (S)	538-592	126-164	200-238	214-256	74-75	88-92	14-18
21 (L)	531-592	121-164	163-206	179-230	41-43	58-66	16-24
22 (U)	539-580	127-153	166-192	184-214	39	57-61	18-23
25 (U)	537-578	126-152	156-188	177-178	30	51-52	21-22

* Soil Field Capacity ♦T = clay, L = loam, U = silt, S = sand **Sim. = Simulation

In case of a melioration of the green spaces the base flow will underestimated by ABIMO with about 10-20 mm/a when the groundwater table is >1m, with 60mm when the groundwater table is <1m.

5. Conclusions

The long-term observation of urban land use change and sprawling land consumption has proven that it is the accumulation of impact, rather than short-term consequences that is likely to impair the urban water balance. The results of the paper show the problems that arise in the long run on the city scale and thus gives an example of how severely urban growth on a city's fringes can affect environmental features such as water balance in quantitative terms. Urban sprawl potentially leads to an increased flood risk produced by increasing direct runoff and a resulting higher release of water out of the urban system. This can restrict a city's chances for future development in that technical precautions necessary to mitigate these problems may become extremely expensive. However, it is fairly clear that the long-term effects of urban sprawl on the environment in general, and water balance in particular, depend not only on the amount but also on the spatial pattern of land conversion, as well as the previous quality of this land (Newman, 2000; Burchell and Mukherji, 2003; Nuissl et al. 2008).

From an environmental point of view, the compact city generally seems to be the most desirable form because it allows the preservation of the largest possible patches of 'natural' landscape. However, an increase of impervious surfaces in existing urban areas tends to be accompanied by a considerable decline in environmental quality there. This was illustrated for the water balance in this paper. Further research concerning the effect of a drop in evapotranspiration on the temperature reducing potential of urban surfaces will be a useful addition to the results presented here in order to integrate scientific knowledge on the long-term urban water balance for spatial planning.

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