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E cological
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ERSEC
International conference
Proceeding

Sustainable Land Use and Water Management

International Conference

Beijing, P.R. China
October 8-10, 2008

Estimating the Diffusion of Decentralized Wastewater and Storm Water Management on the Basis of Land Use Data
基于土地利用数据的分散型废水排放和雨水管理的评估

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Abstract

In Europe and in most other parts of the world, centralized systems of wastewater collection and treatment are state-of-the-art. They and their proper functioning are however questioned by challenges such as climate and demographic change. An alternative to centralized systems of wastewater and storm water treatment and management are decentralized systems, including small-scale treatment plants for wastewater and on-site infiltration of storm water and treated wastewater run-off. However, especially the small-scale treatment plants can face a lock-out by their centralized counterpart. This lock-out is based on arguments that hold in many, but by far not all, conditions and regions. It is important to identify those regions where the alternative, decentralized infrastructure, is not locked out because it tells policy makers and business persons where and when the support and adoption of elements of the alternative approach should best be started.

In order to identify possible starting points for the diffusion of decentralized wastewater and storm water management in the Elbe region, we use geographically differentiated data concerning today's (2004) population, settlement area, sealed surface area, the installed small-scale wastewater treatment devices as well as size and load factors of the existing urban centralized installations. We then and extrapolate these data to the year 2020. It turns out that it is possible to identify regions where the employment of decentralized management of wastewater and storm water, respectively, is much more favorable than in others, and thus adoption of it is much more probable.

摘要

在欧洲和世界上大多数地区，集中式废水收集和处理系统已达到最先进的技术水平。然而这一系统和它固有的功能正面临着由气候和人口变化带来的挑战。针对集中式废水处理和雨水管理系统的一种替代方法是分散型系统，包括小型污水处理厂，现场的雨水渗透以及处理过的污水的排

放。然而，小型污水处理厂尤其可能面临集中式污水处理系统的排斥。这种排斥源于存在的许多争论，但并非所有情况和所有地区都如此。重要的是识别出那些替代性、分散式基础设施没有被排斥的地区，因为这将告诉政策制定者和商业人士在什么地区，什么时间才是支持和采用这种替代方法的最佳时机。

为确认在易北河（Elbe）地区何时何地开始使用分散型污水排放和雨水处理系统，我们使用地理分区不同的数据，综合考虑2004年的人口、居民点、已封存地表、已安装的小型污水处理设备及其尺寸、已有的城市集中型污水处理设备的规模和负荷等，并以此推断出2020年的数据。结论是我们可以识别出采用分散型废水处理和雨水管理系统比其他地区更有利，和采用这种系统的可能性更大的区域。

1 Introduction

In Europe, and in most other parts of the world, centralized systems of wastewater collection and treatment are state-of-the-art. They and their proper functioning are however questioned by a series of challenges. Climate change is in many regions expected to increase the intensity and duration of drought periods in summer and, at the same time, the frequency of heavy precipitation events (Hattermann et al. 2005). The former events hamper the transport of sewage to the treatment plants while the latter lead to the foreseeable release of excess untreated sewage into the natural water bodies. In the context of demographic changes, it is often difficult to adapt the proper operation of the system to population decreases that occur especially in more remote and economically less prosperous regions, e.g., in many parts of Eastern Germany (Koziol et al. 2006). Finally, there is an ongoing tendency towards more efficient water use and decreasing specific water consumption especially in Germany (BGW 2005; Destatis 2006). Although it is not so much a technical problem, these difficulties lead to an increase in total and, all the more, specific operation costs that may not be easily accepted by the served population (Koziol et al. 2006; Hillenbrand/Hiessl 2006). The same argument applies for the high costs of keeping the long-living infrastructure in proper operation.

An alternative to centralized systems of wastewater and, possibly, storm water treatment and management are decentralized systems including small-scale treatment plants for wastewater and on-site infiltration of storm water and treated wastewater run-off. Due to their typically smaller scale, more modular construction and shorter lifespan, both approaches are significantly more flexible and could therefore in principle avoid most of the above mentioned problems. However, the small-scale wastewater treatment plants in particular face a lock-out by their centralized counterparts based mainly on three arguments. Economically, as long as the existing infrastructure represents substantial sunk costs, additional decentralized installations drawing off users from the centralized system increase rather than decrease the specific costs in the first place. As a consequence, operators of the centralized system support, and often refer to, regulation that forces households to remain connected to, and discharge their wastewater into, the conventional system. In addition to increasing returns to adoption, operators of wastewater infrastructure in countries like Germany are directly executing obligations imposed on them by the legislator and as such perceive the conventional system as more controllable and less risky than decentralized systems. Finally, specific costs of urban wastewater treatment plants tend to decrease with increasing size and, thus, seem to outperform small-scale plants. At the moment, all three arguments hold in many, but by far not all conditions. In shrinking cities or regions, for instance, it may be economical to put parts of the existing system out of operation and serve the remaining users with decentralized plants (Koziol et al. 2006; Hillenbrand/Hiessl 2007). The cleaned run-off is then discharged (without further problems) into the former central sewerage or directly into surface waters. In remote places, small-scale plants show a similar performance as large-scale facilities, but at lower costs. In the future, increasing numbers of produced facilities will decrease their costs, such that now, small-scale plants occupy niches of which the number and sizes will increase considerably in the future. In both cases, storm water infiltration and management complement the decentralized wastewater treatment in that they additionally reduce the reliance on a central sewerage for storm water run-off. Because the conditions for a transition are especially favorable in many parts of East Germany, the river Elbe basin was chosen as the region of investigation of this study.

If, for the reasons given, decentralized wastewater and storm water management was indeed increasingly competitive with the conventional approach, policy makers and other actors willing to support the implementation process in an effective manner need to know where and when to best start. In this respect, the approach adopted in this analysis resembles the windows of opportunity approach (see Sartorius/Zundel 2005) with the basic difference being that the window is specified geographically rather than temporally. It also contains elements of the niche management approach (Kemp et al. 1998) insofar as it is assumed that diffusion will start in certain restricted regions with favorable conditions, and will further expand to less favorable regions after acceptance and knowledge have increased, and cost decreased during adoption in the primary niche.

In order to specify a possible starting point for the diffusion of decentralized wastewater and storm water management the proceeding in this paper will be as follows. Section 2 describes the model used to reconcile the supply and demand for wastewater and storm water treatment under a variety of circumstances and specifies in more detail the arguments guiding the diffusion of the technical innovations characterizing a decentralized wastewater and storm water management. Section 3 shows the results of this modeling approach with special focus on the transition from conventional to more decentralized wastewater and storm water management. It also looks at these results in relation to the evolutionary economic literature dealing with path dependency, lock-in, niche management and transition management.

2 Modeling the demand and supply of elements of wastewater and storm water infrastructure

From the techno-economic perspective, it is the primary objective of this paper to identify those regions or locations where the implementation of decentralized wastewater and storm water management is most useful and therefore most probable to start. In order to do this analysis, we apply a model called INNUWIM (INNovation in Urban Water Infrastructure and Management) which is generally used to specify the technical design and the corresponding costs of the wastewater and storm water infrastructure in a given the geographical region (i.e., the Elbe basin) and depending on the existing regulation concerning the degree to which wastewater and storm water have to be treated before being released into natural water bodies.

In order to assess the contributions of various infrastructure components to the effectiveness and cost of the entire infrastructure, INNUWIM uses demand and supply data. The demand for infrastructure is basically determined by the maximum permissible values of relevant emissions (in this case the nutrient elements phosphorous and nitrogen) prescribed by the respective regulation. On the supply side, various technologies may be available by means of which the regulatory limits may be met. Eventually, those technical elements are selected from the available set that brings about the desired effect at the lowest cost under the respective circumstances. This analysis is basically carried out on a rather disaggregate level (i.e., communities or local catchments) and can then be aggregated on the level of interest (e.g., federal, state, or river catchment). Figure 1 shows the structure of the model in which the details are explained below.

Data concerning the number of persons connected to the infrastructure (measured as person equivalents, p.e.), the wastewater volume, the capacities of the treatment plants, the quantities of total phosphate and inorganic nitrogen in the inflows to, and outflows from, the treatment plants, including the corresponding purification performance, were available for all treatment plants with a capacity greater than 2000 p.e. for the year 2004 from the River Basin Community Elbe and for all smaller urban wastewater treatment plants for the year 2000 from the Institute for Landscape Architecture and Environmental Planning at the Technical University in Berlin. All these treatment plants were registered with their exact geographical position and accordingly assigned to their specific local (partial) catchments.

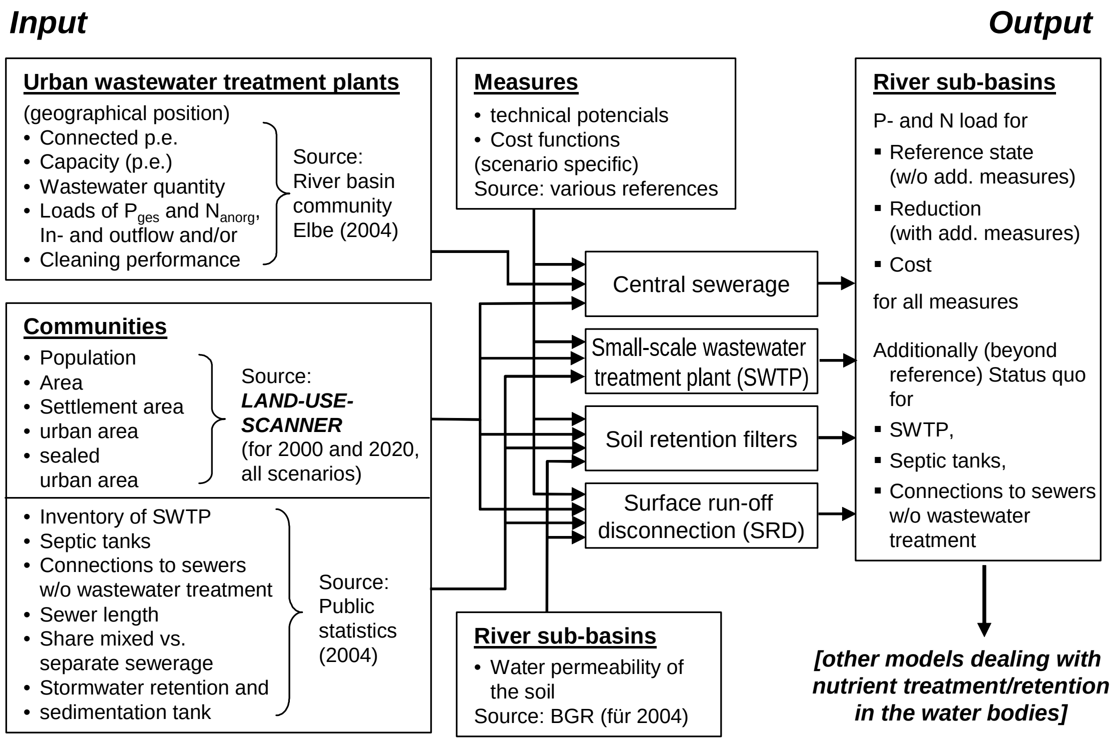

Figure 1: Flow structure of the data in the model INNUWIM determining the influence of the technical specification of the wastewater and storm water infrastructure on costs and effectiveness of the reduction of nutrient emissions

Modeling of the diffusion of small-scale wastewater treatment plants (SWTP) and improvements of the performance of existing installations was based on community-specific data from the statistic agencies of the German states about the quantity of installed SWTP and septic tanks, the number of p.e. the central sewerage, the person-specific length of the sewers and the respective shares of mixed and separate sewerage (all from 2004). Where community-specific data were not available, more aggregated data were disaggregated on the basis of suitable parameters (e.g., number of inhabitants). Part of the more aggregated data came from a survey we had conducted in the beginning of 2006 with the kind support of the German Association for Water, Wastewater and Waste (DWA) (Sartorius/Hillenbrand 2007). From this survey, we could also derive data concerning the actual functional integrity of the SWTP.

Data concerning population quantity, urban, settlement and total area were captured on the community level and used to estimate the extent to which surface areas and the storm water run-off collected on them are available for disconnection from central sewerage. These data stem from the LAND USE SCANNER model, which is able to specify different kinds of land use on a very small scale and project them into the future along different scenarios (Hoymann et al. 2008).

In general, community-specific data are converted to sub-basin-specific data that are more relevant with regard to river basin management. In this context, community-based data are respectively assigned to the sub-basins occupying the largest share of the community area.

Eventually, modeling requires technical and cost figures characterizing different means in the reduction of nutrient emissions from central and (more importantly in this paper) decentralized wastewater and storm water treatment. These figures come from the literature and from expert interviews and are summarized in the following.

2.1 Small-scale wastewater treatment plants

The general conditions for the diffusion of decentralized approaches to wastewater management are based on the scenario A1 of the Intergovernmental Panel of Climate Change (Nakicenovic et al. 2000). This scenario assumes a rather global orientation of the economy and a decreasing intensity of regulation. For Germany this implies that the existing obligation of households to be connected to, and use, the central infrastructure will be abolished. Moreover the subsidization in some German states for connecting even rather remote households to the central wastewater infrastructure will be omitted. Accordingly, the existing small-scale wastewater treatment plants (SWTP) will persist and will possibly be adjusted to a technically state-of-the-art quality. Additionally, a certain proportion of increasing population will also be served by SWTP. This share depends, on the one hand, on the population density and can be derived from the following exponential function

$$\frac{PE_{SWTP}}{PE_{total}} = a \cdot e^{-b \cdot \frac{population}{community \quad area}}, \tag{1}$$

where *a* und *b* (both positive) were empirically assessed from a survey among East-German sewerage operators (Sartorius/Hillenbrand 2007). On the other hand, this share depends on the existence of free capacities in the central urban wastewater treatment plants serving this sub-basin: the lower the free capacities, the stronger the increase in SWTP capacity. Basically the same calculus is applied when SWTP are to replace septic tanks.

If the population shrinks, which is expected to be not uncommon in East Germany, it is assumed that the capacity of SWTP will nevertheless increase. The reason for this is that the central wastewater infrastructure will then work even further below its full capacity and it may be more economical to shut down part of it and serve the remaining people by SWTP. Whether such a shut down occurs crucially depends on the extent of the population decrease and the resulting under-utilization of the existing infrastructure.

According to our assumption a population decrease below 10 percent is not expected to give rise to any shut-down nor to additional SWTP, whereas a decrease of 30 percent or more would result in an increase of the SWTP capacity of 20 percent of the shut-down central capacity.

2.2 Disconnection of surface run-off from central sewerage: water infiltration and unsealing the ground

In the case of central sewerage, systems storm water management includes discharging excess storm water into the natural water bodies. This water is harmful because the surface run-off is contaminated with deposited substances like heavy metals and, in the case of a mixed sewerage system, with wastewater. Alternatively, surface run-off can be disconnected from central sewerage and avoided or treated immediately at its origin. The main components of such a surface run-off disconnection (SRD) are active on-site storm water infiltration into the soil and unsealing of the ground, which avoid the accumulation of run-off water in the first place. The potential for SRD amounts to between 10 and 30 percent in urban areas (Longdong 1999; Wolf/Milojevic 2000) and can reach up to 80 percent in rural areas (Leinweber/Schmitt 2000). The INNUWIM model allows for a maximum SRD rate of 20 percent in existing settlements and 100 percent on newly settled areas. However, the rates chosen as parameters for each model run are not applied uniformly to all communities. Instead, in order to achieve an optimum solution from the macroeconomic perspective, SRD rates are chosen higher where the effectiveness is higher and lower where this measure is less effective.

The effectiveness of the SRD is basically determined by the potential amount of contaminants in the avoided run-off, which is 2.2 and 15.9 kilograms of phosphate and nitrogen, respectively, per hectare sealed surface area and per year (Hahn et al. 2000). These data apply for the employment of SRD measures in newly settled areas and can even be larger in already existing settlements.

In order to calculate the costs of the SRD measures, the specific cost figures of Böhm et al. (2002) for storm water infiltration and unsealing the ground in mixed and separate sewerage systems under different general conditions are applied. Thereby it is assumed that in existing settlements and under unfavorable conditions unsealing of the ground plays a more important role, whereas storm water infiltration is more effective in favorable conditions. In newly constructed settlements neither the cost nor the effect of unsealing the ground are included because, resulting in no additional cost, it is assumed that it will be done anyway. For storm water infiltration the most favorable cost data generally apply. All applied cost data are summarized in Table 1.

Table 1: Costs of the reduction of emissions of the wastewater-based nutrients phosphate and nitrogen for useful combinations of SRD measures in existing and newly constructed settlements (in Euro per gram)

	Measures in existing settlements						… in new settlements		
	Combined system			Separated system					
	favorable	medium	unfavor-able	favorable	medium	unfavor-able	favorable	medium	unfavor-able
P_{ges}	-0,68	1,55	10,96	-1,86	3,88	21,78	-0,75	0,79	2,85
N_{ges}	-0,14	0,30	1,87	-0,26	0,47	2,16	-0,16	0,17	0,59

Finally, it needs to be acknowledged that the effectiveness of SRD measures depends on the water permeability of the soil. In the case of well permeable soils such as sand more simple and less costly installations are sufficient than in the case of less permeable clay. According to Böhm et al. (2002), the difference between both cases amounts to a cost factor of about 2.

With regard to all relevant communities the specific costs (k_{spec}) of the SRD measures are now calculated under the assumption that they (1) increase disproportionately with both the initial (VG) and the eventually aspired degree of unsealing (EG) and (2) change inversely proportionately to the water permeability of the soil (WG) and to the share of separate sewerage (AT). Eventually, the specific costs of the SRD measures can be summarized in the following equation.

$$k_{spec} = (0.5 + 0.65 \cdot AT) \cdot (1 - 0.5 \cdot WG) \cdot (8.5 \cdot e^{4.5 \cdot EG} - 9.9) \cdot e^{VG} \quad (2)$$

In order to achieve cost efficiency for the entire region (in this case the Elbe basin), the achievable degree of unsealing (EG) for a fixed specific cost is determined for every community, eventually yielding an average degree of unsealing for the whole region. Subsequently, the specific cost is modified until the aspired average degree of unsealing is reached. The same procedure is then applied to areas that will be newly settled in the future, taking in account however that in this case the initial degree of sealing and the kind of sewerage system (i.e., separate or mixed) do not play a role.

3 Transition to a decentralized system of wastewater and storm water management

If a variety of different wastewater treatment technologies and their respective contributions to the reduction of, for instance, nutrient emissions into the natural water bodies are compared, it is often implicitly assumed that each of these technologies has an equal chance to propagate, if it is appropriate for the prevailing local conditions and meets the existing regulatory requirements. In this context, it is often overlooked that technical developments do not take place independently of each other. Instead, innovations can impede each other through inherent path dependence and lock-out (David 1985) or support each other through synergistic effects. In order to analyze this kind of phenomena, Dosi (1982) has developed the concept of technological paradigms and trajectories. Within a paradigm technical progress proceeds by gradual improvements and amendments (including end-of-pipe) of existing components, but without changes in the basic structure of the employed technology. Innovations fitting into the paradigm can diffuse quite easily. By contrast, the diffusion of more profound, radical innovations proceeds with much greater difficulty for several reasons. First, the technology as a whole usually finds itself in a much earlier state in the innovation cycle such that adoption of the technology is associated with higher risks in technical as well as economic terms. Second, a less mature technology tends to be produced in smaller quantity with less opportunity for learning by experience; so, it tends to be more expensive. Third, and most importantly, unlike its established counterpart, the radically new technology is not, and may not be able to be, adapted to the existing technical standards and regulatory regime (Zundel et al. 2005).

In the field of wastewater management the contrast between established and radically new technology is best exemplified by the relationship between central and decentralized wastewater treatment. In the Elbe region, like elsewhere in Germany, the central wastewater infrastructure represents the dominant technical paradigm, which, in compliance with the restrictive regulatory regime, guarantees the high quality of wastewater treatment. On the other hand, the high wastewater treatment standards are associated with high costs, when applied generally without regard to the specific circumstances. Due to the long sewers required to connect households, especially in rural areas, investment costs tend to make up a large proportion of the total cost. In general, fixed costs represent 75 percent of the total cost of wastewater treatment. Once invested, these costs will be sunk for the lifetime of the sewerage – that is 50 years and more. From this perspective, the operators of the central sewerage are not in favor of competing (including decentralized) alternatives, when the capacity of their existing facilities is not exhausted. Although the bodies in charge of wastewater collection and treatment (that is, the communities) are public and therefore not subject to private competition, major cost increases cannot easily be passed on to the households for political reasons. Therefore, they try hard to reimburse their costs including a legal obligation of the households to be connected to, and use the central sewerage. Evidently, this undermines private engagement in favor of decentralized alternatives like SWTP that show comparable performance and are in many circumstances much cheaper than the central sewerage. Where such obstacles do not exist, SWTP are in Germany officially considered as an equivalent alternative to central sewerage since 2002 (Supplement 1 of the Wastewater Ordinance).

Against this background, the findings of Sartorius et al. (2008) concerning the potentially positive effect of an extended implementation of SWTP and SRD on the reduction of nutrient emissions in natural water bodies gain an additional significance. Until recently, the existence of SWTP was restricted to small niches and where they existed, considerable attempts were made to further reduce their quantity (compare the results of our survey in Sartorius/Hillenbrand 2007). Only now a rethinking seems to be gaining momentum. In some federal German states in the Elbe basin with many SWTP or septic tanks in operation, governments are forced by the EU Urban Wastewater Directive to repair or replace the existing facilities. As most of these facilities are located in the more remote parts of the country and connection to a central sewerage would tend to be very expensive, the governments of these states seem to recognize the potential of a decentralized wastewater management and adapt their legislation such that an engagement of communities and households in the decentralized technology is much facilitated (MLUR 2001; SMUL 2007; UMV 2007). At this point in time, these activities appear to contribute to the increase of niches that formerly tended to become smaller. Even in the long run, decentralized technologies will be far from a complete substitute for the centralized alternatives. However it is important that existing niches are now allowed to expand at least to some extent, because the learning processes taking place during the niche expansion will probably give rise to improvements with regard to cost and technical performance, such that the future potential of this technology will be further expanded. After a while, both central sewerage and SWTP may be competitors on a level playing field, with each of them prevailing under the respectively favorable conditions.

With the INNUWIM model, the latter development is to be followed up to the year 2020. Currently, only the initial part of the development may have become evident. However, modeling the development will allow for predictions concerning the magnitude of the changes and, more importantly, the regional focal points of the development. In order to identify these regions more clearly, we make use of the expected synergy effects between two innovations jointly characterizing the decentralized management of wastewater and storm water. In the central sewerage system both wastewater and storm water are collected and treated centrally in the wastewater treatment plants and in various supplementary devices such as storm water overflow or sedimentation tanks. In the decentralized regime, SWTP represent only one part of the story. The cleaned wastewater and collected storm water need to be disposed of somewhere and the collected storm water additionally needs to be cleaned. A decentralized approach that nicely complements SWTP and solves most of these remaining problems is storm water infiltration and unsealing the ground – the two elements of SRD. Unsealing the ground avoids the collection of storm water in the first place, and infiltration can be used to dispose of cleaned wastewater or storm water of which the collection is unavoidable.

In order to identify those regions where a transition toward decentralized wastewater and storm water management are most probable, two indices derived from the INNUWIM model are used jointly: the increase in persons connected to SWTP (relative to the total population) and the increase in the sum of infiltrated and unsealed area (relative to the total sealed area). The results for both indices are shown in figure 2 (a and c). Since it is assumed that just the combination of SWTP and SRD represents a reasonable basis for decentralized wastewater and storm water treatment, a composed index was reconstructed by the multiplication of the two above-mentioned indices. The multiplicative composition was chosen in order to make sure that both aspects (SWTP and SRD) make a significant contribution, and that no strong aspect of one can compensate for the weakness of the respective other, as would be the case after addition.[1] Figure 2 (b) shows the regional distribution of the composed index.

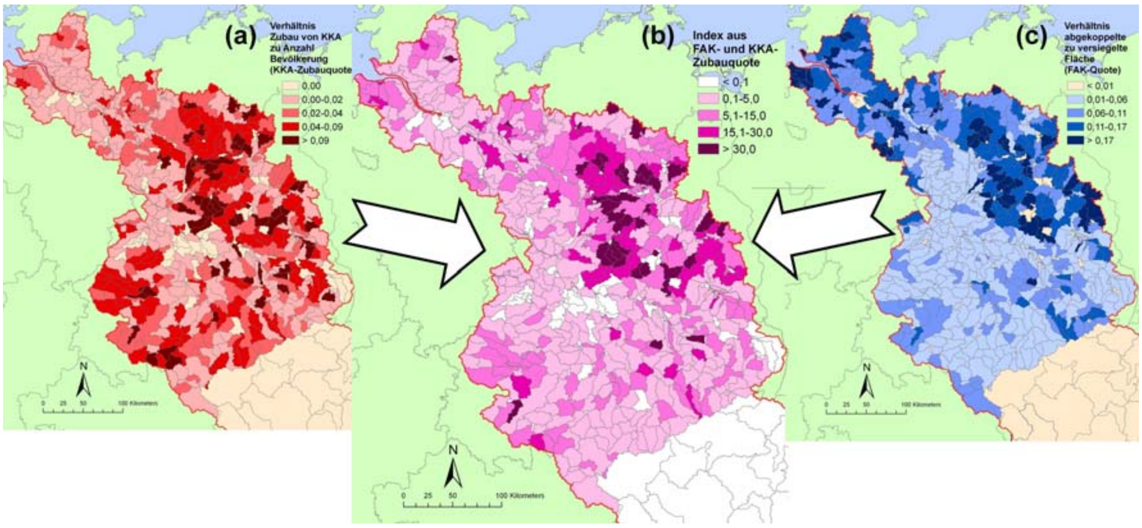

Figure 2: Regional focal points of the transition from central to decentralized wastewater and storm water management. The general tendency (b) is yielded from the multiplicative combination of the diffusion tendencies of SWPT (a) and SRD measures (c).

It is evident that the regional developments of both SWTP and SRD show specific points of focus, some of which they hold in common, some are different. The significant differences between SWTP (focal point in Thuringia) and SRD (focal point in Lower Saxony and Schleswig-Holstein) emphasize that SWTP and SRD are indeed independent aspects of decentralized wastewater and storm water management. The regional overlap of focal points in Brandenburg and Western Pomerania on the other hand shows that an unambiguous focal point for the development of a decentralized wastewater and storm water management exists. Although, due to the longevity of the

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1 Note that the composed index represents a pure index without specific contextual meaning.

established central sewerage system and its institutional background, the hints we find for the emergence of a decentralized alternative in the time period until 2020 are not yet very clear. The potential for such a shift is definitely strongest in the regions identified.

Acknowledgements

The authors thank the German federal ministry for education and research for granting the project GLOWA-Elbe (FKZ: 01LW0308) and the Forschungsdatenzentrum der Statistischen Landesämter (especially in Stuttgart) and the River Basin Community Elbe for providing the data necessary for the model.

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