Innovative low cost procedure for nutrient removal as an integrated element of a decentralised water management concept for rural areas

M. Burde, F. Rolf and F. Grabowski

Brandenburg Technical University of Cottbus – BTUC, Faculty 4 Environmental Science and Process Engineering, Waste Water Treatment Technology, Urban Water Resources Management, Germany

Water Science and Technology: **Vol 44 No1 pp 105–112**

Abstract The absence of large rivers with rather high niveau of self purifying effect in parts of east Germany leads to a discharging of the effluent of wastewater treatment plants into the groundwater in many cases. One useful consequence is the idea of realisation of decentralised measures and concepts in urban water resources management concerning municipal wastewater as well as rainfall, precipitation. At the same time, only the upper soil zone – a few decimetres – is water – saturated and thus discharge effective, even when extreme rainfall takes place. Underneath, however, there generally exists an unsaturated soil zone, which is up to now a rather unexplored retardation element of the hydrologic- and substrate-cycle. Nutrient removal in small wastewater treatment plants that are emptying into ground waters is often beneficial. The presented studies optimised an inexpensive method of subsequent enhanced wastewater treatment. The developed reactor is similar to a concentrated subsoil passage. The fixed bed reactor is divided in two sections to achieve aerobic and anoxic conditions for nitrification/denitrification processes. To enhance phosphorus removal, ferrous particles are put into the aerobic zone. Two series of column tests were carried out and a technical pilot plant was built to verify the efficiency of the process. The results show that this method can be implemented successfully.

Keywords Decentralised water management; water infrastructure; advanced municipal wastewater treatment; unsaturated soil zone; water cycle retardation; rural areas; wastewater treatment; nutrient removal

Introduction, environmental, engineering and planning problem

In summer 1997 there were storms with very large rainfall. Those occurrences contributed to the extremely high water levels of the rivers Oder and Neisse. This again leads to investigations and controversial discussions about efficiency of up to now well known strategies and instruments of catchment-wide urban water resources management – and as a consequence rainfall management and storm water reduction. There is in fact a tendency to look for new, innovative strategies of water resources management concepts that follow the fundamental idea of "decentralisation" concerning water quantity management problem(s).

In rural areas with very low population density, decentralised concepts for wastewater management are common and useful and lead to small treatment plants. Depending on the national legislative standard on environment protection in rural areas wastewater treatment often does not include nutrient removal. In Germany for example, nutrient removal is only obligatory if the treatment plant serves more than 5,000 person equivalents – PE[1]. Depending on the status of the quality situation in a specific river – or lake – catchment, lower water-authorities can formulate more strict advice to eliminate nutrients in treatment plant effluents.

Ecological situation

The hydrological – and water resources management – situation in the federal country of Brandenburg – in the northern part of Germany – is quiet different from the average

[1] In Canada and USA – for example – there exist no equivalent threshold regulations.

boundary conditions in FRG and can mainly be described as follows:

- flat topography, slowly flowing rivers with a low niveau of self purifying effect
- lots of small and flat lakes which have to be treated separately concerning nutrient input
- mainly sandy soil appropriate to high percolation rate which leads to disappearance of the small receiving watercourses in summer as a consequence of periods with rather low precipitation
- lowering of the groundwater levels caused by surface-coal-mining which cover large areas and lead to smaller rivers run dry
- the end of artificial/man-made (ground) water-cycle-management as an integrated element of the conversion of surface-coal-mining areas causes dry running of artificial receiving waters.

There is a dominant loss of larger rivers that have a qualitative and quantitative efficiency/capacity to empty the effluent of wastewater treatment plants in those receiving bodies of water into the underground – this means the unsaturated and saturated zone of the subsurface soil/underground.

There is a strong connection on the one hand between wastewater management and the near surface groundwater (Burde, 1992a) and on the other hand between precipitation and river catchment-wide water management concept(s).

Then very fast flow of large rainfalls from sealed surfaces in municipalities and from landscapes without or with only little water storage capacity outside small villages into rivers causes storm water events and threatens the whole ecosystem.

Specific legislative guideline

National law

According to the fundamental principles of long-term preservation of the environment within the hierarchical structured system of (ecological and spatial) planning in Germany, the water authorities in the *Land* of Brandenburg have set up very strict and precise guidelines concerning urban water resources management and especially wastewater treatment in rural areas on the one hand and long-term securement of groundwater quality on the other hand.

Because nobody knows quite enough about the biological/biochemical mechanism of pollutant input, transport, degradation, metabolisation and – last not least – reduction in the underground, it is absolutely necessary to fulfil the fundamental principles of "long-term preservation safeguarding of groundwater quality" (Burde, 1992b).

As a consequence – even in rural areas, far away from enlarged settlement areas or urban centralised agglomerations – extensive nutrient removal is required by environmental law.

In case of percolating the following annual averages are prescribed:

BOD_5: 7 mg/l ; COD: 30 mg/l ; $N_{total\ anorg}$: 13 mg/l ; P_{total}: 0.7 mg/l

these legislative demands have been derived from the maximum concentrations that are tolerable in raw water that is used for drinking water supply.

The demands correspond with the fundamental principles of long-term safeguarding of the quality of the near surface groundwater layer – (ground) water being the most important foodstuff – according to the principles of existence – preservation in spatial and ecological planning. Comparable demands do not exist for large and very large wastewater treatment plants if emptying their effluent in receiving streams.

Guideline of the European Community (EC)

In the (so called) "water guide line" (in German, Wasserrahmenrichtlinie or WRRL) – that has been developed by the European Community as a proposal – it is demanded: ". . . to develop an integrated water management concept for a river catchment that takes all belongings of

- the surrounding ecosystems
- the plain use of landscape
- social and socio-economical impacts into account (Burde, 2000).

Starting point of project realisation

The leading idea of project realisation within a river catchment is to combine the two strategies of decentralisation as leading elements of one comprehensive landscape water resources management concept.

To fulfil the task of extensive nutrient removal in rural areas, with small, decentralised wastewater treatment plant(s), a specific purification procedure was developed (in the cause of research and development activities at the Chair of Waste Water Technology at Brandenburg Technical University Cottbus – BTUC) according to the following assumptions, boundary conditions and objectives:

- conventional, for rural regions suitable treatment technologies are used for basic sewage purification
- advanced purification facilities should establish a long-term stable process with minimal energy consumption, maintenance and capital expenditure
- denitrification process is supported by the use of degradable organic agriculture wastes as carbon sources (Müller *et al*., 1985)
- phosphorus removal is improved by integrating waste products containing ferric compounds into the running purification process (Thole, 1993).

It is one of the project's aims, to percolate the treatment plant's effluent into the underground instead of emptying into a river (or lake) without threatening the quality of the groundwater.

As a consequence, a good quantitative effect on groundwater management is realised. The effluent water stays a much longer time within the water cycle – the discharge amount is lowered. Even when extreme rainfall takes place, only the upper soil zone of a few decimetres magnitude is water saturated and thus discharges effectively.

Underneath however there generally exists an unsaturated soil zone, which has up to now an unacknowledged potential for water retention within the water cycle of a landscape (or river catchment) (Sieker, 1996, 1998b).

The post-war development of land use outside and far away from large settlement areas or urban centralised agglomerations, especially agricultural land use in F.R.G. e.g.

- frequent drainage of wet arable land and permanent grassland,
- physical soil degradation, . . .

and more accompanying effects – described in Ploeg, van der and Sieker (2000) – led to a loss of soil/landscape infiltrability and water storage capacity and induced as a consequence more surface runoff.

A purposeful and systematic change/alternation in agricultural land use, as for example

- tilling techniques (conservation tilling),
- use of heavy and ultra-heavy machines,
- drainage activities . . .

will bring back and reactivate favourable runoff properties. (Ploeg, van der, 1998a)

Implementation, basic concept

Surface runoff is recognised to have increased on a large scale, and the causes of increased runoff are well known. As a consequence rational measures can be taken to reduce it.

- Decentralised rainwater management can effectively reduce surface runoff in urban areas (Sieker, 1996),

- Decreasing the intensity of soil drainage may help to reduce subsurface runoff from agricultural land (Ploeg, van der, Ehlars and Sieker, 1999)
- Expanding the area of conservation tillage is another possibility for reducing surface runoff.

Although it may take years to recover from the past physical soil degradation, meadow soils will eventually regain some of their former favourable properties. In addition to increasing infiltrability and reducing runoff, reconversion measures will also help reduce the eutrophication of surface water, such as that in lakes and streams.

So, one part of the water cycle retardation effect is, to decrease (fast) surface runoff into rivers. The other part is, to bring the effluent of treatment plants into the groundwater/the underground – and not into rivers – for groundwater enrichment and to have another retardation effect on water and substrate – especially nutrient – cycle for example in a catchment area.

Through the impoundment of one part, the wastewater purifying reactor – consisting of solid degradable organic material – is divided into an anoxic and an aerobic layer – filled with ferrogenious particles – iron(III) ions are released by oxidative processes.

The oxygen supply is optimised concerning the above mentioned process and no excess oxygen prevents formation of anoxic milieu in the second part of the reactor.

Experimental set-up and first results

Pre-experimental series were carried out with six column reactors – filled with different materials and operated under adapted test conditions – about seven inches high with 0.7 inch diameter.

Inert materials are used at the bottom of the filter column to prevent contamination of the sewage caused by excessive decomposition.

During the first test period, the different contents of the reactor columns – where sampling points at vertical intervals of 1 dm are placed – were straw chaff, wooden chips, bark mulch and peat.

Concerning the fate of organic compounds the following could be recognised:

- COD-runoff ranges from 60 to 120 mg/l
- recontamination of sewage by decomposition in straw- filled columns
- very low BOD-concentrations in the effluent of wood- and bark-filled columns
- unusual COD/BOD ratio (more than twice that of common wastewater treatment) obviously caused by undegradable wooden lignin substances
- successful nitrification over a whole years' range (below temperatures of 10 degrees effluent less then 5 mg/l NH_4-N)
- denitrification depends strongly on availability and degradability of organic fixed bed material
- the fundamentally limited phosphorus removal potential depends on the frequency of renewing of the reactor filling as described.

Figure 1 shows the pre-experimental test unit.

Conclusions of the first estimations

The analysis within this research (and development) project suggests

- that innovative concepts of water resources management will help to solve problems caused by periods of very intensive rainfall and the connected effluent amount(s)
- expanding the area of conservation tillage is a possibility for reducing surface runoff
- that another strategy to reduce the threat of stormwater events along rivers is to reconvert former grassland from arable land into meadow
- that meadow soil will eventually regain some of its former properties concerning increasing infiltrability and reducing runoff.

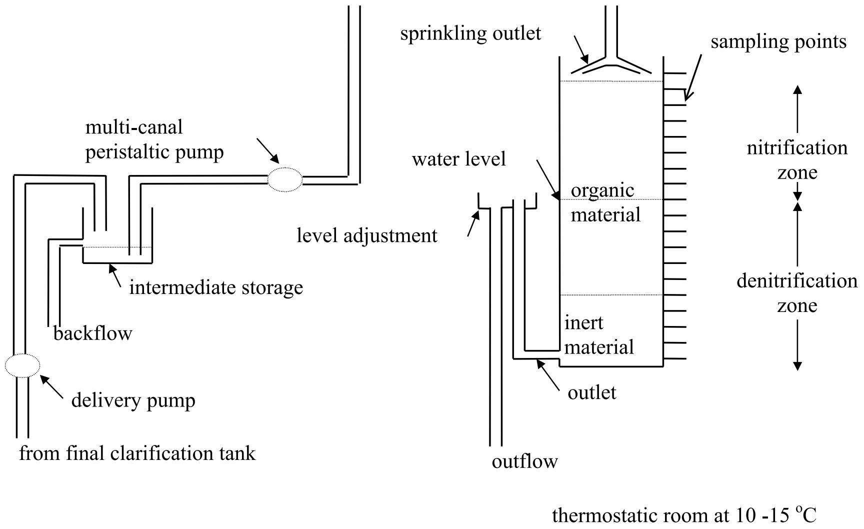

Figure 1 Experimental set-up

The pre-experimental series with the test-reactor – filled with degradable organic material – showed that the elimination of organic compounds, nitrification and phosphorus removal are processes which are feasible under conditions similar to the test. To reach a higher rate of denitrification it is necessary to separate the aerobic and anoxic zone. The anoxic zone must be directly accessible to refill the organic material. The passage of this material through the aerobic zone eliminates the degradable compounds and hinders sufficient denitrification. Under these changed conditions straw chaff seems to be a suitable organic material. The high degradability of straw chaff could be controlled by the regulation of the contact time.

Enhanced test unit

Based on the results described, a modified and improved test unit (see Figure 2) was built to enhance ammonia oxidation and to buffer ammonia loading peaks we included an additional 5% zeolite stone to build the aerobic section (Witte and Keding, 1992). Furthermore 0.1% ferrous particles were added in order to improve phosphorus removal (Thole, 1993).

The flow direction in the aerobic section was still vertical. In the anoxic section we chose a horizontal flow to achieve the possibility of changing the active volume of the reactor. This could by executed through adjusting the water level by changing the height of the outflow tube. The anoxic zone was extended by a sand filtration unit (Eichinger *et al.*, 1995). This compartment was added to reach a complete anoxic reaction and minimise the BOD outflow concentration.

The retention time in the aerobic zone was two hours. In the anoxic zone it was 1 to 6 hours depending on the water level.

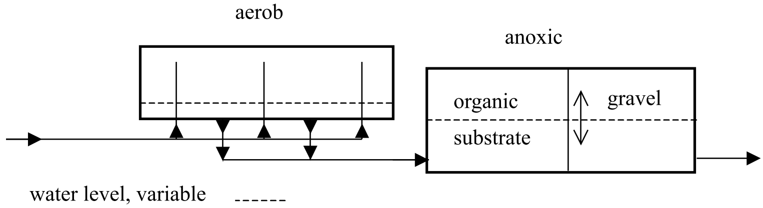

Figure 2 Flow chart of the enhanced test unit and the technical plant

The second test drive was carried out under the aspect of extensive denitrification. Suitable organic substrates and simple routines for maintenance were tested.

During the test drive we used two organic substrates, chopped straw and a mixture of different flax plant parts. After a ripening-in time of around 2 weeks the degradation began. It reached its highest rate in another 2 weeks. We lowered the water level and achieved a sufficient denitrification for about 6 months. Step by step we raised the water level to enlarge the anoxic zone. This way we compensated the loss of substrate through advanced degradation. The procedure offers a simple facility to control the process.

The rates of nitrification and phosphorus removal reached over 90%. The average outflow concentration of ammonia was less than 3 mg/l. The Phosphate-P outflow concentration remained below 0.5 mg/l.

In order to find the actual required arrangement, especially the adequate anoxic reactor volume, it is only necessary to test the nitrate and BOD outflow concentration. For these tests a rapid method seems to be sufficient. When these values have been obtained, the adequate adjustment of the outflow level is simple. The investigation showed that after the ripening time a weekly control seems to be sufficient.

Technical scale pilot plant

To demonstrate the efficiency and feasibility of this process under real condition, we built a technical scale pilot plant. The pilot plant was erected in Zinnitz, a village with 300 inhabitants. The present treatment plant was about to lose its artificial receiving water. The suggested solution, infiltration of the effluent into the ground water, requires forcing up the purification capacity considerably. Particularly extensive nutrient removal is required by law. In case of percolation Brandenburg country prescribes the following annual averages: BOD < 7 mg/l, COD < 30 mg/l, $N_{total\ anorg}$ < 13 mg/l, P_{total} < 0.7 mg/l.

During 3 months in the spring and summer 1997 the plant was planned and constructed. The same flow system was used as in the enhanced test unit which is shown in Figure 2. The reactor is designed for a specific hydraulic load up to 4 $PE/m^2 \cdot d$. The average hydraulic load of the aerobic section is around 0.5 $m^3/m^2 \cdot d$.

The aerobic zone is filled with 95% lava stone, 5% zeolite stone and 0.1% ferric wastes. The anoxic section is divided into two lines. One line contains 60% straw and 40% sand/gravel, the other line 40% straw and 60% sand/gravel.

Results (of the ripening-in phase and the beginning of the pilot plant operation)

The load used initially was 2 $PE/m^2 \cdot d$, which corresponds to a hydraulic load of around 200 $l/m^2 \cdot d$. The retention time in the aerobic zone could be estimated as 2.5 hours. We started the test operation with an anoxic reactor volume of around 20 m^3 in both lines. The initial height of the water level (0.4 m) was lowered when the effect of degradation was observed. Currently we have adjusted the water level in line one to 0.2 m, in line two to 0.25 m.

The nitrification rate is about 95%. Phosphorus removal is also effective and amounts to 90%. The denitrification is complete, while the concentration of BOD (around 30 mg/l) has not reached the desired low level. We are continuously reducing the anoxic reactor volume in order to decrease the organic substrate load and find a better balance between substrate supply and nitrate flow.

As soon as a satisfactory stable process is established, the first extensive measuring program was started.

Conclusions

- The reported results show that advanced purification in small treatment plants can be achieved inexpensively by subsequent treatment in an optimised filter reactor.

- The aerobic processes, nitrification and phosphorus removal by absorption, caused no problems. We measured elimination rates higher than 90%.
- The capacity of phosphorus removal is principally limited. After the consumption of the ferric ions the reactor filling has to be renewed.
- Denitrification greatly depends on the availability of a degradable organic substrate. Degradable agricultural wastes like chopped straw and flax are suitable.
- To balance the substrate load and the nitrate flow a variation of the reactor volume by a simple device is practicable.
- A weekly test on BOD and nitrate seems to be sufficient to find an appropriate adjustment.

Outlook

We have seen in the last decade, that none of the innovative systems is going to be realised if it is not required from a superior institution (Burde, 1998; 1999a).

The realisation of the described measures and instruments on water disposal infrastructure have economical, ecological and sociodemographical effects, fits into other regional, national and European – not only environmental – policies for example concerning agenda 2000, principles of sustainability and has a very innovative character. In the near future it should be discussed, in which way the evaluated methods are transferable to other similar planning situations and regions, compare Ostrowski (1997).

References

Adler, R., Landmann, J. and Cameron, D. (1993). *The Clean Water Act 20 Years Later*. Island Press, Washington DC.

Burde, M. (1992a). *Zur Bestimmung von Wasserqualitätszielen für die Regionalplanung,* Vortrag auf der fachöffentlichen Sitzung der Sektion I – Umwelt und Wirtschaft – der Akademie für Raumforschung und Landesplanung – ARL – Hannover; am 30./31. März 1992, "Umsetzung ökologischen Wissens in die regionalplanerische Praxis" ; Würzburg.

Burde, M. (1992b). *Die vorsorgende und langfristige Grundwassersicherung durch die Ausweisung von Grundwasservorranggebieten als gemeinsame Aufgabe von Raumplanung und Fachplanung*; Dissertation im Fachbereich Architektur, Raum- und Umweltplanung, Bauingenieurwesen der Universität Kaiserslautern; Schriftenreihe des Fachgebietes Siedlungswasserwirtschaft, Bd. 5.

Burde, M. (1998). *Was kann die Regionalplanung zum vorsorgenden Hochwasserschutz beitragen?*; Seminar/Symposium „Vorbeugender Hochwasserschutz durch dezentrale Maßnahmen im Bereich der Siedlungswasserwirtschaft und der Landwirtschaft; 06./07. Oktober 1998; St. Marienthal/Ostriz, Neisse, gefördert von: Deutsche Bundesstiftung Umwelt (DBU), Osnabrück.

Burde, M. (1999a). *Katalog von Planungsunterlagen für die Ausweisung von Vor-ranggebieten und Vorbehaltsarealen zur Realisierung dezentraler Systeme der Be-wirtschaftung von Niederschlagswasser für Innovativen, vorsorgenden Hochwasser-schutz auf Ebene der Landes(entwicklungs)- und Regionalplanung*, unveröffentlichtes Manuskript, Projekt Nr. 15788 der Deutschen Bundesstifung Umweltschutz, Lehrstuhl Abwassertechnik/Siedlungswasserwirtschaft, Brandenburgische Technische Universität Cottbus.

Burde, M. (2000). *Verwendung der Planungsgrundlagen für die Ausweisung von Vorranggebieten bzw. Vorbehaltsarealen zur Realisierung dezentraler Systeme im Rahmen eines mehrstufigen Planungsprozesses – katalogartige Zusammenstellung,* NATO-Seminar Internationaler Hochwasserschutz; 8. bis 12. 11. 2000; Ostritz, St. Marienthal.

Eichinger, J., Kramer, P., Böhm, B. and Wilderer, P.A. (1995). *Subsequent denitrification in a sand filtration unit*. In Wasser & Boden 5/95 47 10–14 (German).

Müller, W.-R., Sperandio, A. and Erne, M. (1985). *Denitrification with biological degradable fixed bed material for advanced wastewater treatment*. In Landwirtsch. Forschung 38 132–138 (German).

Ostrowski, M.W. and Obermann, J. (1997). *Grundlagen und Werkzeuge zur ganzheitlichen wasserwirtschaftlichen Planung,* Wasser und Boden, 49 Jg., Heft 5/1997, S. 61 bis 65.

Ploeg, van der, R. (1998a). *Deintensivierung in der deutschen Landwirtschaft als eine dezentrale Maßnahme zur Hochwasserreduzierung*, in: Sieker (1998b).

Ploeg, van der, R., Ehlers, W. and Sieker, F. (1999). *Floods and other possible adverse environmental effects on meadowland area decline in former West Germany*; Naturwissenschaften 86, 1999.

Ploeg, van der, R.R. and Sieker, F. (2000). *Bodenwasserrückhalt zum Hochwasserschutz durch Extensivierung der Dränung landwirtschaftlich genutzter Flächen,* Wasserwirtschaft; 2, 2000.

Sieker, F. (1996). *Dezentrale Regenwasserbewirtschaftung in Siedlungsgebieten: ein Beitrag zur Dämpfung extremer Hochwasserereignisse?* Geowissenschaften 14: 531–538.

Sieker, F. (1998a). *Thesenpapier*; in Sieker (1998b).

Sieker, F. (1998b, Hg.). *Dokumentation zum Workshop „Hochwasserreduzierung durch dezentrale Maßnahmen?“*, durchgeführt im Rahmen des von der Deutschen Bundesstiftung Umwelt geförderten Forschungsprojektes „Hochwasserreduzierung durch dezentrale Maßnahmen“, Hydrologische Untersuchungen im Einzugsgebiet der Saar unter Beteiligung der Gemeinden Rehlingen-Siersburg, Bous, Beckingen und Weiskirchen hinsichtlich baulicher Umsetzungen, am 15./16. Mai 1998 in Weiskirchen/Saarland.

Thole, S. (1993). *Phosphorus Removal in Public Wastewater Treatment Plants Using Ferruginous Waterwork Sludge.* VDI Reihe 15 Nr. 117. VDI-Verlag, Düsseldorf (German).

United Nations (1993). *Protection of Water Resources and Aquatic Ecosystems.* Water Series No. 1. ECE/ENVWA/31 United Nations Publication, New York.

Witte, H. and Keding, M. (1992). *Zeolite Filters in Wastewater Treatment Plants*. In: Chemical Water and Wastewater Treatment II. Springer-Verlag Berlin.