Bioremediation, phytotechnology and artificial groundwater recharge: potential applications and technology transfer issues for developing countries

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Summary

Bioremediation, phytotechnology and artificial groundwater recharge have proven effective in industrialized countries. They also have great potential for use in the developing world. Mimicking naturally occurring processes, they provide solutions that are environmentally sustainable. When these and other technologies are applied in developing countries, social, economic and environmental conditions need to be taken into account at the local level. Issues related to technology transfer and capacity building should also be adequately addressed.

Résumé

Si la biodépollution, les phytotechnologies et la recharge artificielle des nappes phréatiques ont montré leur efficacité dans le monde industrialisé, elles offrent aussi des possibilités considérables dans les pays en développement. Imitant des processus naturels, elles apportent des solutions tout à fait viables du point de vue de l'environnement. Mais lorsqu'on applique ces technologies et d'autres dans des pays en développement, il faut tenir compte du contexte social, économique et environnemental local. Il faut aussi s'attaquer aux problèmes de transfert de technologie et de renforcement des capacités.

Resumen

En los países industrializados se ha demostrado la eficacia de la biorremediación, la fitotecnología y la recarga artificial de acuíferos. Estas tecnologías también tienen un gran potencial para ser aplicadas en los países en desarrollo; al imitar procesos naturales, brindan soluciones ambientalmente sostenibles. La aplicación de éstas y otras tecnologías en países en desarrollo exige la consideración de las condiciones locales en términos sociales, económicos y ambientales. Asimismo, es necesario revisar adecuadamente cuestiones relativas a la transferencia de tecnología y al fortalecimiento de capacidades.

We are all too aware of the statistics revealing the diminishing availability of good quality water and the increasing threat that this poses to the health and life of humans and other life forms on earth.[1] The evidence for this is obvious in cities in developing countries. The way we manage our water is unsustainable.

Figure 1 shows current practice, with waste water from industry, municipal waste water, stormwater and municipal solid waste being discharged into rivers and seas. The result is pollution of the receiving water, making it very poor quality for humans (water not fit for swimming or other contact recreation) and for the aquatic organisms on which we depend for our existence.

One way to deal with this situation involves collecting municipal solid waste and burying it (landfilling), and collecting waste water and stormwater in a sewerage system and treating the collected waste water. Solids (sludge) separated from the treatment of the waste water are landfilled or incinerated; or they may be applied in agriculture as biosolids (Figure 1), in which case nutrients (nitrogen and phosphorus) are returned to nature as fertilizers. But the sludge is usually contaminated by industrial waste (e.g. heavy metals such as cadmium and nickel). Furthermore additional nutrients are still required for agriculture, and these are obtained through manufacture of chemical fertilizers. Phosphate rock is mined, imported and processed into superphosphate. Nitrogenous fertilizers are manufactured from atmospheric nitrogen.

These activities require significant amounts of energy, with corresponding impacts on the environment. Note that the flow of materials (e.g. phosphorus and nitrogen) is one-way: towards the receiving environment, polluting it. Note also that pollution of water is a result of materials that are not originally in the water, but transported with it. Water is the conveying agent for pollution of the receiving water environments.

Technology exists to treat the waste water to remove pollutants down to very low levels. This approach is costly and the pollutants invariably end up with the sludge. Figure 2 shows a better way to manage the water cycle.

In this approach industrial waste is treated separately from municipal waste, thus preventing contamination of municipal waste by industrial waste (upper right hand corner of figure). Industrial waste should be reused and recycled in accordance with the waste management hierarchy: first, avoid producing waste; second, minimize what cannot be avoided; third, recycle/reuse what waste is unavoidable; and, finally, treat any remaining residue for safe disposal. Cleaner production techniques should be explored to assist in putting the waste management hierarchy into effect.

Stormwater should be separately collected and treated because it is likely to be less polluted. In the example shown in Figure 2 stormwater infiltrates into the ground and is a means of recharging aquifers. This is feasible where the soil is permeable. As the water infiltrates through the ground, large particulates are removed and bacterial action degrades them. There are other ways to manage the collected stormwater, such as the use of wetlands and ponds, which can also provide amenities for recreational purposes.[2]

Municipal solid waste should be collected and managed separately. Techniques are available to recycle aluminium, ferrous metals, plastic, glass and paper. The organic fraction of municipal solid waste should ideally be composted and the compost applied in agriculture. This will return organic carbon to the soil along with the fertilizer value of organic waste (nitrogen and phosphorus).[3]

Municipal waste water consists of grey water and black water. Grey water is water from bathing and washing, whereas black water is water from the toilet. The latter contains much of the fertilizer value in municipal waste water, but also human pathogens. In the example shown in Figure 2, grey water is treated using wetlands while black water is subjected to digestion treatment to produce biogas (a mixture of methane, CH_4, and carbon dioxide, CO_2), which is a source of energy. The solids left after digestion are applied in agriculture, again returning to the environment the fertilizer value of the waste by using it to produce food, which in turn is a major source of the nitrogen and phos-

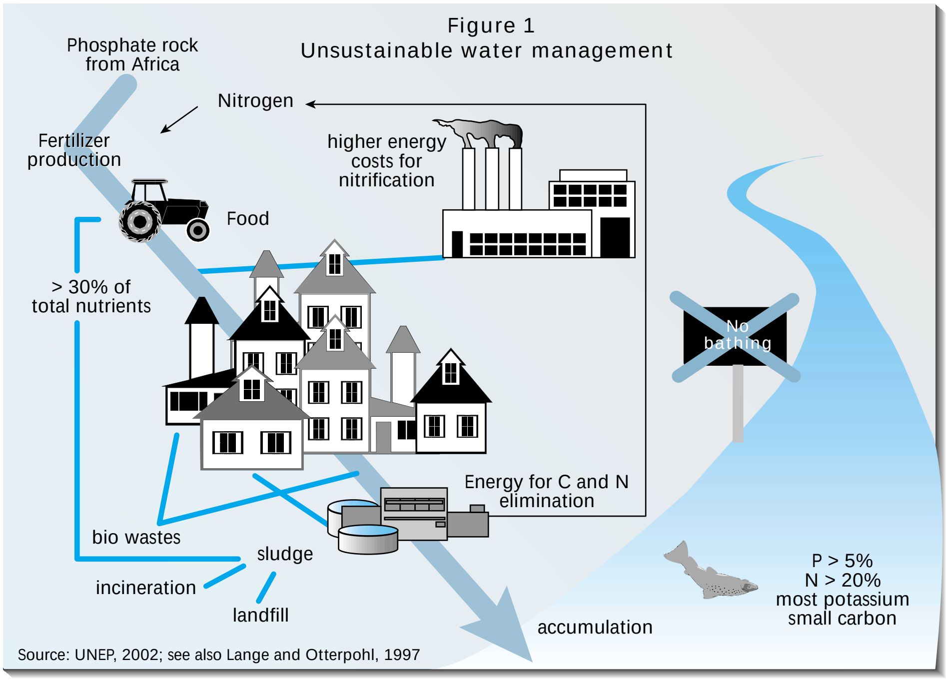


Figure 1
Unsustainable water management

Source: UNEP, 2002; see also Lange and Otterpohl, 1997

phorus in municipal waste water. We thus close the nitrogen and phosphorus loops and prevent contamination of our waters. The result is good water quality in our environment for humans and aquatic organisms.

The ideal picture shown in Figure 2 will take time to achieve in industrialized countries, which have adopted a management approach along the lines shown in Figure 1, with infrastructure such as sewerage and treatment plants that have a fairly long lifetime. Developing countries, however, can adopt the more sustainable management systems shown in Figure 2 without having to go through the high water and energy use stage shown in Figure 1.

The main message relating to sustainable development of industry is to manage waste separately from municipal systems and adopt the waste management hierarchy and cleaner production techniques, the aim being ultimately to achieve clean production with zero waste and close the cycles of all materials. By using this approach we don't have to solve problems, we avoid generating them in the first place.

In the meantime, though, we must deal with the numerous sites in developed and developing countries that have been contaminated by pollutants, and with groundwater reservoirs depleted by extraction rates that exceed natural recharge. Much progress and knowledge have resulted from remediating polluted sites and restoring the water balance of aquifers. This article discusses three techniques that can have wide applications in developing countries because they rely on processes that mimic those occurring in nature. These are bioremediation, phytotechnology and artificial groundwater recharge. The technology transfer issues that need to be addressed for adoption of these techniques in developing countries are also discussed.

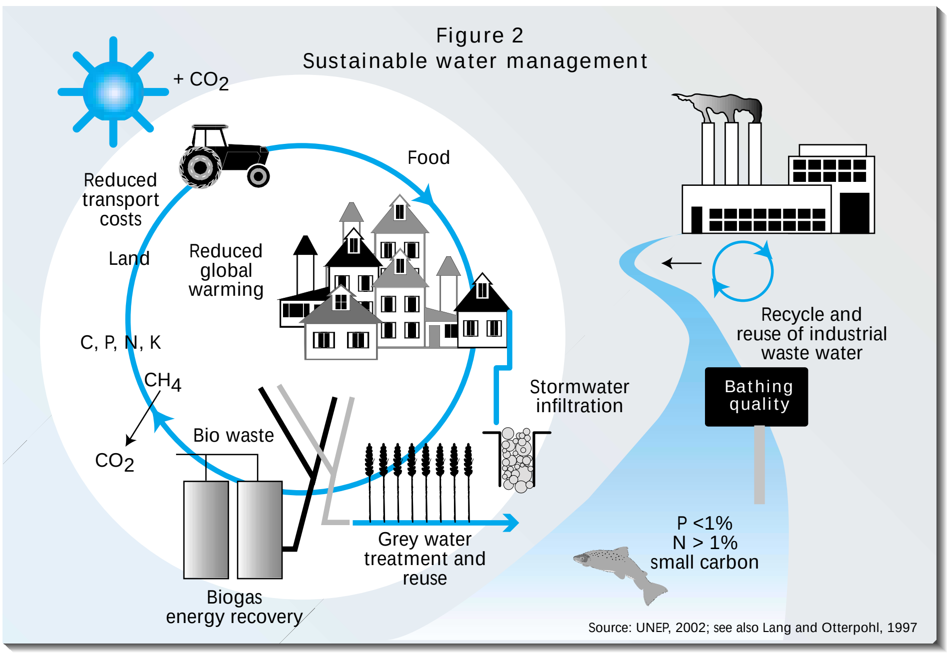


Figure 2
Sustainable water management

Source: UNEP, 2002; see also Lang and Otterpohl, 1997

Bioremediation

Natural processes in the environment recycle materials in such a way that there is a dynamic equilibrium which maintains life on earth. An example is the carbon cycle (Figure 3). Carbon dioxide in the atmosphere is taken up by terrestrial and aquatic plants for photosynthesis. Photosynthesis produces the building blocks of plant materials, which are a source of food for animals. Plant and animal excretion, litter, and dead plants and animals are decomposed by a host of microorganisms, returning the carbon to the atmosphere; or they accumulate over very long periods as peat, coal or oil.

Decomposition of organic materials also releases other elements such as nitrogen, phosphorus and sulphur, which are made available to plant roots and become part of other natural cycles (e.g. the nitrogen cycle, phosphorus cycle and sulphur cycle). We should note that in a pristine natural environment, such as an undisturbed forest, the water quality of streams and groundwater is very good. To a large extent this is because of the activity of microorganisms.

Naturally occurring microorganisms (bacteria, fungi, protists) breaking down organic materials, and active in the natural carbon and other cycles, can also break down contamination by substances such as sewage, crude oil, petrol from leaking storage tanks, kerosene, jet fuel, nitrogen from fertilizer, and even small quantities of toxic chemicals such as chlorinated solvents used in heavy industry, pesticides used in agriculture, and creosote used in preserving wood. For specific examples, case studies and further information, refer to the bioremediation site suggested in the References.

Using naturally occurring microorganisms is a great advantage because they are available freely. At contaminated sites, however, conditions are generally not favourable for these microorganisms. Compost may have to be added, for example, to provide the organic carbon required by the microorganisms. In other cases nitrogen, phosphorus and other nutrients may be required to provide more balanced "diet" for the microorganisms. Sometimes air is required to provide them with oxygen, and surfactant may need to be added to emulsify the soil to increase surface area availability. These measures add costs to the use of bioremediation. Enhanced bioremediation, which utilizes microorganisms that have been developed or selected for particular types of organic action, can be costly as well.

We should also recognize the limitation of bioremediation. Microorganisms cannot survive in high concentrations of toxic chemicals or salt; nor can they destroy heavy metals. In these cases chemical and other methods should be considered.

Phytotechnology

The use of plants to improve environmental quality is widely known and accepted, and can be more widely applied in developing countries. Plants can be used for:

◆ landscaping industrial sites to provide amenities for employees, visual barriers and buffer zones

from residential areas, as well as for water reuse;
- rehabilitation of areas affected by soil erosion;
- restoration of mined areas (e.g. surface mining);
- treatment of stormwater;
- treatment of waste water.

In many cases the plants so used can be harvested to produce timber, bio-energy and animal feed, or in wider or longer-term applications, e.g. reforestation to increase the sink for the greenhouse gas CO_2.

The term phytotechnology refers generally to the application of science and engineering to examine problems and provide solutions involving plants.[4] While there are many applications of plants, as indicated above,[5] the focus here is on the use of plants for pollution control, and in particular for the treatment of industrial waste that is organic in nature (e.g. abattoir waste, food processing waste). It should be emphasized, however, that treatment of waste is one of the lower rungs of the waste management hierarchy, and that first every attempt should be made to avoid, minimize, reuse and recycle. There are many opportunities to carry these out in industries generating organic waste.

An outstanding example of a phytotechnology that can have wide application in developing countries is the use of wetlands (Figure 4). The wetlands can be existing ones carefully selected as suitable for the purpose, or (more commonly) constructed wetlands. Artificial wetlands are built by digging a hole, lining it with an impermeable barrier (such as high-density polyethylene plastic sheets) to prevent water from percolating through the soil, and laying gravel in it as a medium for plant roots. Suitable wetland plants (fast-growing, tolerant to high nutrients), preferably ones indigenous to the area, are then planted in the gravel.

As waste water is passed through the wetland biological purification takes place very much as in the case of bioremediation. Much of the degradation of the organic pollutants in the waste is due to the activities of microorganisms. Plants aid in providing oxygen to the root zone, in taking up nutrients and in immobilizing a number of pollutants (e.g. heavy metals) by uptake. This technology is appropriately called phytoremediation. To reduce the potential for mosquito breeding, the level of water in the wetland should be maintained below the surface so that there is no water ponding.

Another example of phytotechnology is soil filtration (Figure 5). Here waste water is allowed to filter through the soil in a slightly inclined field. As the water percolates through the soil, purification by natural soil microorganisms takes place. Plants (usually grasses) also take up nutrients. Thus the purification process is similar to that taking place in a constructed wetland.

An additional benefit of soil filtration is that the grass can be grazed by sheep, goats and cattle. It is important that toxic chemicals such as heavy metals not be introduced, so application is limited to waste water from industry which does not generate toxic materials. There is, however, still a wide potential application for waste water from abattoirs and food processing as long as it is not mixed with other industrial waste water. The only factor that then needs addressing is the risk of pathogen transmission.

A key to the success of the application of phytotechnology, phytoremediation, bioremediation and indeed any technology is the correct design, construction, operation and maintenance of the technology. With correct implementation, possible risk, including from the transmission of pathogens, is minimized or reduced to very low levels. On the other hand, incorrect implementation may result in undertreatment and risks of disease transmission.

Artificial groundwater recharge

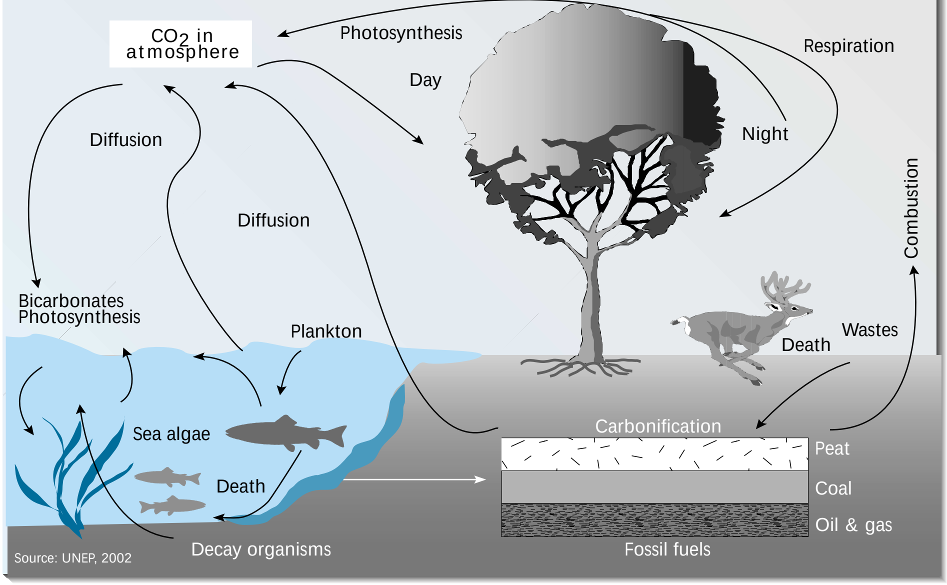
Groundwater is normally recharged by rainfall (either recent or from more distant areas and times). It should only be withdrawn below the rate of recharge, so that the resource is used sustainably. In many parts of the world groundwater is now used far above the level of sustainability. This has resulted in the lowering of the water table. Wells have to be deepened to mine the water. As a result, in coastal areas there has been encroachment of salt water, making the groundwater unsuitable for use. In some areas lowering of the water table has resulted in uneven ground subsidence and damage to infrastructure (roads, buildings).

Artificial groundwater recharge is the augmentation of natural recharge. Sources of water can be stormwater (Figure 2), grey water and treated waste water. Recharge can be through a well drilled to the groundwater aquifer, or through recharge basins. The former requires water of a higher purity to prevent clogging of the recharge wells. The latter may have wider application in developing countries.

Figure 6 shows a schematic diagram of groundwater recharge using treated waste water. The treated waste water is introduced into unlined basins, allowing the water to percolate through the soils to the groundwater aquifer. During percolation, microorganisms degrade and transform organic substances in the water in the same way as in a bioremediation process. The use of multiple basins is essential, as the bottom of the basins become clogged with time and a rejuvenation period is required during which water is diverted to rejuvenated basins. In the drying period the organic and bacterial mat is dried by the sun, allowing regeneration of the infiltration rate.

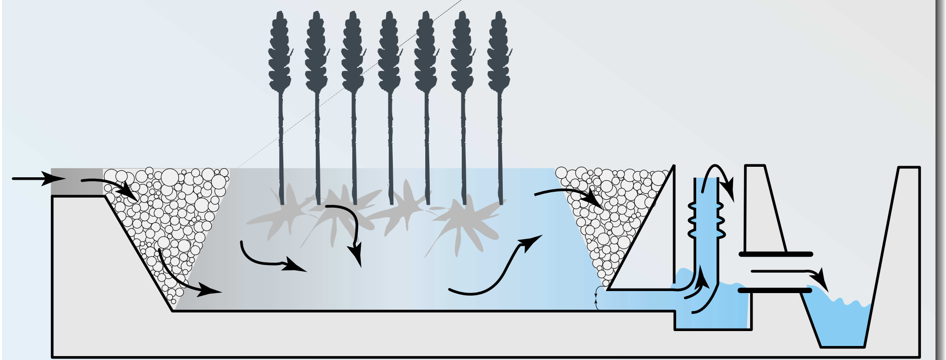
Clearly artificial groundwater recharge can only

Figure 3
The carbon cycle



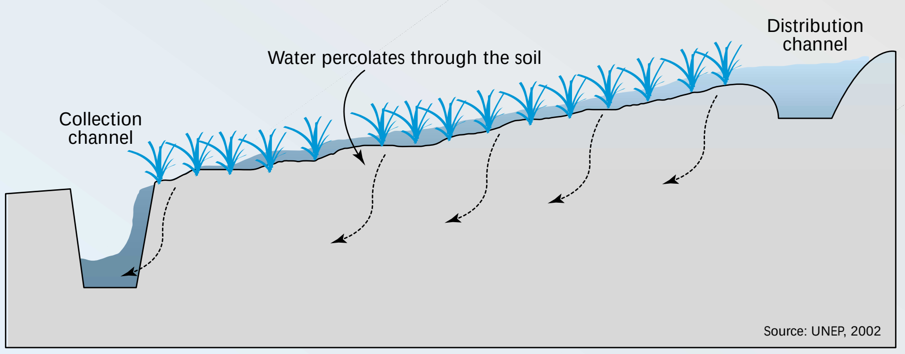
Source: UNEP, 2002

Figure 4
Wetland waste water treatment: a phytotechnology with wide potential for application in developing countries



Source: UNEP, 2002

Figure 5
Soil filtration of waste water: another phytotechnology with wide application in developing countries



be used in areas where the soil and geological conditions are appropriate (unconfined aquifer, sufficiently permeable soils and underlying formation). Fortunately these are the same conditions that often give rise to excessive groundwater withdrawal, because of ease of access to the water.

Technology transfer issues

Bioremediation, phytotechnology and artificial groundwater recharge are examples of technologies that would be appropriate for developing countries because they rely on (and indeed mimic) natural processes. The capital and operating costs of these technologies can expected to be lower than purely engineered systems. On the other hand, these technologies require land area.

Beyond the conventional consideration of the technology itself and the costs (or economics) of implementing the technology, there are broader issues pertaining to the context of applying technologies in the local social, environmental and cultural situation of specific developing communities. These issues include:

◆ providing quality information on technology, so that communities can make informed decisions;
◆ facilitating involvement of local community members in decision making, so that the technology selected fits in with the local social, environmental, economic and cultural conditions;
◆ building capacity on the part of decision makers in central, regional and local governments, so that there is consistent policy, and support for local implementation of the most appropriate technology for the local community.

These are system considerations which go beyond technology to the interface between technology and society. The right choice of technology in the system context can lead to sustainable development, and the wrong choice can lead to unsustainable development. One response to the challenge posed by this issue is provided by UNEP's International Environmental Technology Centre.[6] It has developed:

◆ a technology database containing information on technology, information systems/sources and institutions;
◆ tools for assessing the soundness of environmental technology, including criteria that should be employed;
◆ training modules in many areas of technology, including electronic-based training modules, to supplement face-to-face training;
◆ partnerships in information delivery and capacity building.

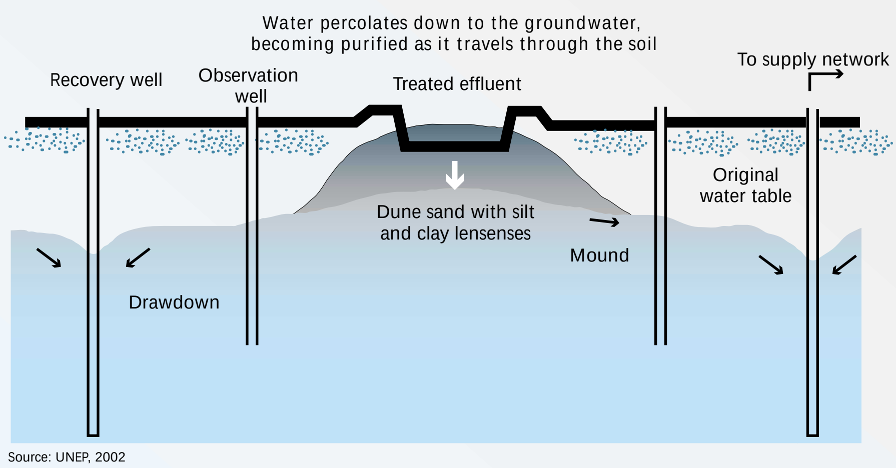
The effectiveness of any of these means, individually and in concert, should be continually assessed. A process of evaluation has commenced. In due course it will become clearer how the issues in technology transfer, and hence choice of technology, can be addressed.

Conclusions

Bioremediation, phytotechnology and artificial groundwater recharge have been shown to be effective technologies in industrialized countries and can have wide application in developing countries. These technologies mimic natural processes of purification and fit in with the concept of environmental sustainability discussed at the beginning of this article.

The application of these and other technologies in developing countries will need to consider specific local social, economic and environmental conditions. Tools have been developed to assist with carrying out this process systematically. Clearly there is a need to transfer this knowledge to decision makers and to build local capacity, and we need to strive harder to meet this need.

Figure 6
Artificial groundwater recharge with treated waste water



Notes

1. UNEP IETC (2003) *Sustainable freshwater management, information technology and technology transfer*, UNEP International Environmental Technology Centre (IETC), Osaka (www.unep.or.jp/ietc/focus_on_ietc/index.asp#1206).
2. UNEP (2002) Environmentally Sound Technologies for Wastewater and Stormwater Management – An International Source Book, International Water Association Publishing and UNEP IETC, London and Osaka (www.unep.or.jp/ietc/Publications/TechPublications/TechPub-15/main_index.asp).
3. UNEP (1996) *International Source Book on Environmentally Sound Technologies for Municipal Solid Waste Management*, UNEP International Environmental Technology Centre, Osaka (www.unep.or.jp/ietc/ESTdir/Pub/MSW/index.asp).
4. UNEP IETC (2003) *Phytotechnologies – A technical approach in environmental management*, UNEP International Environmental Technology Centre (IETC), Osaka (www.unep.or.jp/ietc/Publications/Freshwater/FMS7/1.asp).
5. Ibid. Also see related publications listed in this reference.
6. UNEP IETC, *Sustainable freshwater management*.

The Environmental Technology Centre is a Centre of Excellence in industry-focused research and development. It is a UNEP International Environmental Technology Centre Cooperation Centre. See www.etc.murdoch.edu.au.

References

In addition to the publications cited above, see J. Lange and R. Otterpohl, *Oekologie Aktuell Abwasser Handbuch zu einer zukunftsfaehigen Wasserwirtschaft*, Mallbeton GmbH, Donaueschingen-Pfohren, 1997.

A useful start for finding resources on bioremediation is www.enviroliteracy.org/article.php/625.html and the links contained therein.

For information on artificial groundwater recharge, see www.iah.org/recharge/links.html. ◆