nanotechnology, water development

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An electronic copy of this paper can be downloaded at: http://www.merid.org/nano/waterpaper.

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executive summary

Nanotechnology encompasses a broad range of tools, techniques, and applications and is widely perceived as one of the most significant technologies of the 21st century. Engineered nanomaterials are manufactured materials with a structure between approximately 1 nanometer (nm) and 100 nm. Their unique physicochemical (e.g., size, shape) and surface (e.g., reactivity, conductivity) properties contribute to the development of materials with novel properties and technical solutions to problems that have been challenging to solve with conventional technologies.

Nanotechnology for water purification has been identified as a high priority area because water treatment devices that incorporate nanoscale materials are already available and human development needs for clean water are pressing. This paper describes:

- How lack of access to clean water and sanitation is affecting millions of people;
- The broad range of issues people confront when implementing projects for improving access to clean water;
- Specific water treatment devices that incorporate nanotechnology; and,
- Potential opportunities, risks, and other issues associated with these technologies.

This paper brings together a unique set of information that demonstrates the range of complex issues that need to be considered and addressed in applying technology, including nanotechnology, for improving basic sanitation and access to clean water. As an increasing number of initiatives explore the use of nanotechnology for development, now is the time to discuss the broad set of issues that need to be considered as these technologies are developed. This paper is intended to help inform those discussions.

The paper includes two case studies describing projects designed to improve access to clean water – one in Bangladesh that uses a conventional water treatment approach and one in South Africa using a device that incorporates a nanofiltration membrane. The case study from Bangladesh describes a low cost and simple approach using sari cloth for removing cholera bacteria from water. "The success of the project is evaluated against social, economic, and environmental criteria. The case study in Bangladesh illustrates the range of issues that must be considered when developing projects for improving access to clean water; these issues are equally important for projects that incorporate nanotechnology and those that do not. The Bangladesh case study, therefore, helps the reader assess a project in South Africa, which is described in section 4, that uses nanofiltration membranes for treating water in a rural village.

Water and Development

Section 1 describes the complex set of well-documented social, economic, and environmental issues that contribute to and result from the lack of access to clean water and sanitation. The data underscores that access to clean water and sanitation are basic elements for any strategy to eliminate poverty and improve people's livelihoods.

In 2002, 1.1 billion people lacked access to a reliable water supply (e.g., 40% of people in Africa lacked access to a reliable water supply), and 2.6 billion people lacked access to adequate sanitation (e.g., 50% of people in Asia lacked access to adequate sanitation). The consequences of lack of access to clean water and adequate sanitation are overwhelming:

- Lack of drinking water and sanitation kills 4,500 children a day, mostly as a result of waterborne diseases;
- Many children miss school because neither their homes nor schools have adequate drinking water or sanitation facilities;
- Hundreds of millions of African, Asian, and Latin American families lose vital income from the lack of access to reliable drinking water and sanitation services (meeting the MDG[1] target for clean water and sanitation is estimated to yield economic benefits close to USD 12 billion a year).

Poverty and water are closely linked and access to water resources has become widely equated with ensuring that basic human needs are met. It is predominantly the poor of the world who depend directly on water and other natural resources for their livelihoods. People depend on water in four key ways: as an input into production to sustain livelihoods to maintain health and welfare and to ensure ecosystems integrity. Water resources must be managed in a sustainable manner in order to maintain the economic, social, and environmental functions it provides in contributing to the livelihoods of people.

Given the importance of access to clean water and basic sanitation for eliminating poverty and improving people's livelihoods, people around the world have made it a priority to develop practical and appropriate approaches for improving access to clean water and basic sanitation.

Case Study of a Simple Water Filtration Method for Cholera Prevention in Bangladesh

With information about the severity and significance of the water and sanitation challenge as a backdrop, the case study in section 2 gives an example of a simple, affordable, and reportedly successful

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[1] The United Nation's Millennium Development Goals (MDGs) set a target to halve, by 2015, the proportion of people without access to safe drinking water and basic sanitation.

technology designed to remove cholera bacteria from water. While this paper is focused on the application of nanotechnology to water treatment devices, the inclusion of the Bangladesh case study, which features a non-nanotechnology approach for water treatment, illustrates the range of issues that must be considered when developing projects for improving access to clean water. These issues are important for projects that incorporate nanotechnology and those that do not.

The case study, which features an approach using sari cloth to filter cholera bacteria from water, illustrates the broad range of economic, social and environmental issues that have to be addressed when implementing projects in developing countries to improve access to clean water and basic sanitation. This approach, which does not utilize nanotechnology, also enables comparison to the project featured in the South African case study (section 4) that utilizes a nanofiltration membrane.

Cholera and other diarrheal diseases are major killers, especially for children in developing countries. It is estimated that approximately 5.5 million cases of cholera are diagnosed annually. In countries such as Bangladesh, tubewells that tap into groundwater are expected to provide safe drinking water but studies indicate that they fail to protect against gastrointestinal diseases.

Boiling water prior to drinking helps kill pathogens, but it is time-consuming and may be expensive in countries where there is a shortage of fuelwood. Bottled water is a suitable alternative in developed countries but it is too expensive to be a viable option for people who suffer from waterborne diseases.

Since cholera is dose dependent, filtration is a practical method for reducing cholera in areas where people must depend on untreated water. This case study documents an experiment using four layers of sari cloth as the filter, which provides a simple and inexpensive method to remove 99% of cholera bacteria from water.

A community-based study was targeted to underprivileged rural populations and sought to reduce cholera by directly involving the local community. Approximately 45,000 villagers were asked to participate in the trial, in three groups of 15,000 each.[2] A first group was asked to use the sari filter, a second group was provided with nylon filters, and a third group was used as a control.

Four months after the system was introduced to the villages, 90% of the population accepted the sari filtration system into their daily lives. The field trial indicated that there was a significant reduction in the cases of cholera in the groups using the nylon and sari filtration systems. The group using the sari filtration method had 48% less cholera cases than the control group (i.e., cholera was reduced by about half). The success of this project, illustrated by the data above, speaks to the attention given by project sponsors to issues such as cost, ease of use, and effectiveness. Projects that involve the use of nanotechnology would need to be sensitive to these issues as well.

It was clear that sari filtration contributed to bringing safer water into houses without any additional cost to the household, resulting in significant health benefits to people who have very few other alternatives. The sari filtration method was evaluated using a multi criteria analysis that traces improvements in the three sustainable development indicators: economic efficiency (net monetary benefits), social equity (improved benefits for the poor), and environmental protection (reduced water pollution). Sari filtration satisfied the economic, social, and environmental criteria, while being readily accessible to the public, even after extreme weather conditions such as the monsoons. The evaluation model is described in more detail in annex 1, and is applicable to other projects using technologies to clean water.

The case study authors suggest that simple purification materials such as sari cloth, perhaps suitably treated or impregnated with nanotechnology-based materials, could filter more effectively and further increase health benefits.

Nanotechnology Water Treatment Devices

Given the importance of clean water to people in developed and developing countries, numerous organizations are considering the potential application of nanoscience to solve technical challenges associated with the removal of water contaminants. Technology developers and others claim that these technologies offer more effective, efficient, durable, and affordable approaches to removing specific types of pollutants from water. A range of water treatment devices that incorporate nanotechnology are already on the market and others are in advanced stages of development. These nanotechnology applications include:

☐ Nanofiltration membranes, including desalination technologies;
☐ Attapulgite clay, zeolite, and polymer filters;
☐ Nanocatalysts;
☐ Magnetic nanoparticles; and
☐ Nanosensors for the detection of contaminants.

Each type of technology, and specific examples for each type of technology, is described in detail in section 3.

Nanofiltration and Desalination

Nanofiltration membrane technology is already widely applied for removal of dissolved salts from salty water, removal of micro pollutants, water softening, and wastewater treatment. Nanofiltration membranes selectively reject substances, which enables the removal of harmful pollutants and retention of nutrients present in water that are required for the normal functioning of the body. It is expected that nanotechnology will contribute to improvements in membrane technology that will drive down the costs of desalination, which is currently a significant impediment to wider adoption of desalination technology.

Source materials for nanofilters include naturally occurring zeolites and attapulgite clays, which can now be manipulated on the nanoscale to allow for greater control over pore size of filter

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[2] This project of testing cholera devices was completed in advance of this paper; the project was implemented by the International Centre for Diarrhoeal Disease Research, Bangladesh (ICDDR,B) and funded by the National Institute of Nursing Research of the National Institutes of Health, United States, not by the GDNP.

membranes. Researchers are also developing new classes of nanoporous polymeric materials that are more effective than conventional polymer filters.

New filters and desalination devices that incorporate nanotechnology are already on the market, and new discoveries are being published practically every week and could soon result in even more efficient, effective, and cheaper filters.[3]

Nanocatalysts and Magnetic Nanoparticles

Researchers expect that nanocatalysts and magnetic nanoparticles will enable the use of heavily polluted water for drinking, sanitation, and irrigation. Using catalytic particles could chemically degrade pollutants instead of simply moving them somewhere else, including pollutants for which existing technologies are inefficient or cost prohibitive. Magnetic nanoparticles, when coated with different compounds that have a selective affinity for diverse contaminating substances, could be used to remove pollutants, including arsenic, from water. Companies are commercializing these technologies and researchers are frequently publishing new discoveries in this area.

Nanosensors

Researchers are developing new sensor technologies that combine micro- and nanofabrication technology to create small, portable, and highly accurate sensors to detect chemical and biochemical parameters in water. Several research consortia are field testing devices that incorporate nanosensor technology to detect pollutants in water, and some expect to commercialize these devices in the next year. New research results are published frequently.

Risks and Other Issues

While much attention has been focused on the potential benefits of water treatment devices that incorporate nanotechnology, a growing number of people are advocating for more research to assess the potential human health and environmental risks of nanotechnologies. Current estimates indicate that investments in environment, health, and safety research are a small percentage of overall investments in nanotechnology R&D (e.g., in the US 4% of the total USD 1.1 billion is invested in EHS research).

Although there are a limited number of research studies on the potential human health and environmental risks of nanotechologies, some research indicates that the unique properties of nanomaterials (e.g., size, shape, reactivity, conductivity) may cause them to be toxic. Because research on the impacts of nanomaterials is limited, risk experts are looking to the results of studies with incidental and natural nanoscale particles and studies with airborne ultrafine particles as the basis for the expanding field of nanotoxicology.

Many people have also suggested that a coordinated risk research agenda should be developed to ensure that the right questions are being asked and resources are used efficiently. In addition to a lack of knowledge about the human health and environmental effects of nanoscale materials, common frameworks for risk research, risk assessment, and risk management are lacking; several organizations are working to fill these gaps. The challenges related to assessing and managing the potential risks of nanoscale materials are relevant to people in both developed and developing countries. Therefore, it is imperative that information about potential risks and risk management approaches is shared widely.

In addition to potential risks, a number of social issues need to be addressed in developing projects that incorporate nanotechnology. As further illustrated in the case studies, information and education about water quality, in particular about contaminants that cannot be detected by observing the water's physical properties (i.e., smell, taste, color), are needed to make communities aware of the actual quality of their drinking water. Furthermore, water service providers, government, and the community should all be involved from the planning to the implementation stages of a community water treatment project to enhance transparency and dispel distrust between the parties.

Case Study of a Nanofiltration Method in South Africa

The South African Nanofiltration Case Study describes a project using nanofiltration membranes to provide clean drinking water to rural communities. It demonstrates that developing countries are applying nanofiltration technology to meet their citizen's needs. This is a project initiated by the South African government and implemented by researchers from a South African university. The case study is set in North West Province, a semiarid region of South Africa. The majority of people in the rural area depend on groundwater or borehole water for their livelihood. Some groundwater sources are contaminated with inorganic nitrogeno us pollutants, chloride, fluoride, calcium, and magnesium ions, which are a health risk to people in these rural communities.

North West University (NWU) obtained a research grant from South Africa's Water Research Commission to conduct a research project to test a nanofiltration membrane technology unit for the removal of nitrate, chloride, phosphate, and sulphate ions pollutants from groundwater[4] and to monitor rural consumer knowledge of and attitudes toward water purification.[5]

Four flat-sheet nanofiltration (NF) membranes and a reverse osmosis (RO) membrane were selected for the water treatment study. The membranes were tested in a laboratory to enable the selection of the membrane most appropriate for contaminated groundwater in the village where the water treatment device would be deployed. Following the laboratory characterization, on-site water treatment studies were carried out with the water treatment plant. The plant, which is compact and easily transportable, is also easy to operate and maintain, and has built-in safety features.

In conjunction with the technical project, NWU conducted a study to determine consumer understanding of the implementation of a water treatment project, identify aspects that needed to be

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[3] The searchable archives of Nanotechnology and Development News provide convenient access to overviews of relevant publications on nanofiltration, nanocatalysts, magnetic nanoparticles, and nanosensors: http://www.merid.org/NDN/archive.php.

[4] NWU Mafikeng campus

[5] NWU Potchefstroom campus

addressed in an educational program on water treatment, and develop, implement, and evaluate a water treatment education program. The involvement of the community from the outset and providing the community with the necessary information regarding basic water services resulted in the acceptance of the water treatment project and in community ownership of the service. Community members have shown a preference for the filtered water.

In addition to the direct humanitarian benefits of improving access to clean water, the technology highlighted in this case study can also promote economic viability in rural communities. A research student who has been working for the pilot project plans to acquire an identical system to install in her village.

Conclusion

Nanotechnology applications for water treatment are not years away; they are already available and many more are likely to come on the market in the coming years. The paper shows that nanotechnology research is being conducted in a broad spectrum of areas relevant to water treatment, including filters, catalysts, magnetic nanoparticles, and sensors. However, the maturity of research and development efforts is uneven across these areas, with nanofiltration currently appearing most mature. Interest in the application of nanotechnology for water treatment appears to be driven by several factors including, but not limited to, reduced costs, improved ability to selectively remove contaminants, durability, and size of the device. While the current generation of nanofilters may be relatively simple, many researchers believe that future generations of nanotechnology-based water treatment devices will capitalize on the new properties of nanoscale materials. Advances through nanotechnology, therefore, may prove to be of significant interest to both developed and developing countries.

Developing countries are – on their own initiative – pursuing these technologies for both economic and humanitarian reasons. As the South African case study illustrates, developing countries are using existing nanotechnology products and are initiating nanotechnology projects to remove pollutants from water; the use of these technologies is not limited to developed countries. It is not clear, however, how widely these technologies are being used in developing countries. Furthermore, while many developing countries are pursuing nanotechnology for economic reasons, the South African case study highlights a project that is being implemented to meet a humanitarian need.

This paper describes the range of issues that must be considered when developing and implementing a water treatment project using nanotechnology. While the issues described in the Bangladesh case study are of significant importance to any project designed to improve access to clean water, projects incorporating nanotechnology are likely to raise specific questions about potential environmental and human health risks. The South African case study, for example, touches on these issues. The limited review of potential risks may reflect a confidence among project sponsors about the safety of the device used in the case study. It may, however, also indicate a relative lack of information about the risks of nanotechnology, especially information specific to water treatment devices.

This paper is intended as a resource to help people understand the severity of the water and sanitation problem in developing countries, the issues confronting people trying to address this challenge, and the potential opportunities and risks of using nanotechnology to improve sanitation and access to clean water. It is also intended as a resource for participants in a workshop on nanotechnology, water, and development, which Meridian Institute is convening in 2006. The objective of the workshop will be to develop recommendations that will inform decisions and catalyze actions by stakeholders involved with:

- ☐ Nanotechnology research and development efforts relevant to providing clean water in developing countries.
- ☐ Activities to address potential environmental, health, safety, socio-economic, and other issues related to the use of nanotechnology to provide clean water.

In developing these recommendations, workshop participants will discuss a range of questions including, but not necessarily limited to the following.

- ☐ What are the barriers to improving sanitation and access to clean water in developing countries?
- ☐ How can science, technology, and existing knowledge help address these challenges?
- ☐ What potential does nanotechnology present for addressing these challenges?
- ☐ To the extent that nanotechnology presents opportunities, are there risks and other issues that need to be addressed?
- ☐ What can be done to catalyze or accelerate activities that address these opportunities and risks?

We invite your insights about these questions and feedback about the following paper.[6]

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[6] Comments can be sent to nanowater@merid.org.

introduction

Nanotechnology encompasses a broad range of tools, techniques, and applications and is widely perceived as one of the most significant technologies of the 21st century. Engineered nanomaterials are manufactured materials with a structure between approximately 1 nm and 100 nm. Their unique physicochemical (e.g., size, shape) and surface (e.g., reactivity, conductivity) properties contribute to technological breakthroughs that enable new and improved technical solutions to problems that have been challenging to solve with conventional technologies.

Nanotechnology is being applied to many areas (e.g., medicine, energy, agriculture) but from a human development perspective water purification has been identified as a high priority. Water treatment devices that incorporate nanoscale materials are already available, and human development needs for clean water are pressing. Given the interest in the issue of water, nanotechnology, and development, this paper explores the scale and significance of water and sanitation problems in developing countries, the broad array of challenges associated with improving access to water, and the possible opportunities and risks of using nanotechnology to address these challenges.

Section 1 provides an overview of development needs regarding clean water,[7] including a description of issues and challenges of providing clean water in poor communities. The section places the use of clean water technologies in a larger social, economic, political, and cultural context. Section 2 provides a case study of a conventional technological approach for removing a specific contaminant from drinking water in Bangladesh. The case study illustrates the many factors that need to be considered when developing technological approaches that are appropriate to local conditions. The sari filtration technique to remove cholera bacteria from drinking water is reportedly a very simple, affordable, and popular water treatment strategy. The author of this case study speculates about the potential for nanotechnology to enhance this conventional technology.

Section 3 describes potential opportunities and risks of four different categories of water treatment devices that incorporate nanotechnology. This section includes detailed information about these categories of devices, including companies and research institutions working on developing new products as well as information about research into the potential human health and environmental risks, and socioeconomic issues of these technologies. Section 4 describes a case study that focuses on a water filtration plant for rural communities in South Africa, which uses nanofiltration membranes to provide potable water. This case study provides a description of an existing effort using nanotechnology to assist poor communities in accessing clean water and describes a possible approach for using nanotechnology to provide sustainable benefits to communities.

The paper was commissioned as part of the Global Dialogue on Nanotechnology and the Poor: Opportunities and Risks (GDNP).[8] The paper contributes to the GDNP goals of raising awareness about the implications of nanotechnology for developing countries and identifying specific opportunities and risks associated with nanotechnology applications, especially those with potential applications in developing countries. In addition, the paper is intended to inform a workshop that will help inform decisions and catalyze actions by a broad range of stakeholders interested in the development of water treatment devices incorporating nanotechnology and individuals focused on identifying and addressing potential environmental, health, and socioeconomic issues.

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[7] Clean water includes water that is safe to drink and available in sufficient quantities for hygienic purposes and may include water that is sufficiently clean to use for other purposes (e.g., irrigation water might include organic nutrients but should not contain toxins).

[8] Detailed information about the GDNP is available at: http://www.merid.org/nano.

[I] water and development

Historically, water has played a critical role in every facet of human activity. In more recent times, water has emerged as a key natural resource to be efficiently managed for sustainable development. Water is vital in a modern economy, not only in the urban-industrial context but also in rural areas through its more widespread use in productive activities and its potential to improve living conditions.

Faced with a shortage of capital, as well as the need to improve the economic efficiency, social equity, and environmental sustainability of projects, the role of the water resource decisionmaker is becoming increasingly more demanding. It is clear that sustainable development can be achieved only by a comprehensive framework that systematically integrates water-related social, economic, environmental, and technical considerations within the broader framework of a national development strategy.

[I.I] Global and Regional Status of Water Supply

In the 21st century, many countries are entering an era of severe water shortage.[9] Increasing competition among agricultural, industrial, and domestic users will lead to clashes and significant increases in the real cost of water. Table I shows that the largest user of water is irrigated agriculture, accounting for 70% of global water withdrawals in 2000, while the respective shares of industrial and domestic usage were 20% and 10%. Agricultural use dominated globally (70%) and in developing countries (88%). Meanwhile, the share of industrial and domestic use increased with rising country incomes, while agricultural use declined.

Table I: Relative Water Withdrawals by Sector in 2000

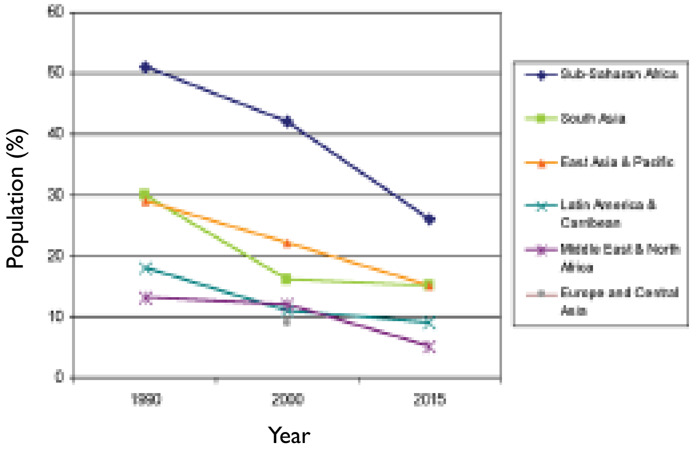
Country Group	Water Consumption as Share of Total Use		
	Domestic	Agriculture	Industry
Low Income	6%	88%	5%
Middle Income	10%	70%	20%
High Income	15%	41%	44%
World	10%	70%	20%

Source: World Resources Institute, 2000.[10]

The poor are most affected by the lack of potable water, which is the focus of this paper. During the decade of 1990 to 2000, the percentage of people served with some form of reliable water supply rose from 79% (4.1 billion) to 82% (4.9 billion). Over the same period, the proportion of the world's population with access to sanitation facilities increased from 55% (2.9 billion people served) to 60% (3.6 billion).[11] At the beginning of 2002, one-sixth (1.1 billion people) of the world's population did not have access to a reliable water supply, and two-fifths (2.6 billion people) lacked access to adequate sanitation.[12] The majority of these people live in Asia and Africa.

In sub-Saharan Africa, 300 million people lack access to reliable water sources. South Asia has made exceptional progress, but contamination of water sources poses new risks. In East Asia, rapid urbanization is posing a challenge for the provision of water and other public utilities. Figure I shows the percentage of the population without access to reliable water sources, by region, and the predicted values for 2015.[13]

Figure I: Population without Access to Reliable Water Sources (Actual Values 1990, 2000; Estimated 2015)



Source: World Bank, 2003.

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[9] M. Munasinghe, *Water Supply and Environmental Management*, Westview Press, Boulder, CO, 1992a.

[10] P. H. Gleick, *The World's Water 2000-2001: The Biennial Report on Freshwater Resources*, Island Press, Washington DC, 2000.

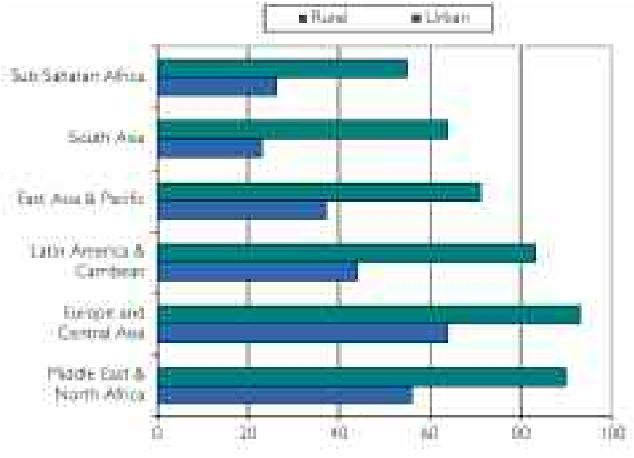
[11] World Health Organization (WHO) and United Nations Childrens Fund (UNICEF), *Global Water Supply and Sanitation Assessment 2000 Report*, 2000.

[12] World Health Organization (WHO) and United Nations Children's Fund (UNICEF), *Water for Life: Making It Happen*, 2005.

[13] World Bank, *World Development Indicators 2005*, 2005.

Although the greatest increase in population will be in urban areas, the worst levels of coverage at present are in rural areas (see Figure 2). In Africa, Asia, and Latin America and the Caribbean, rural coverage for sanitation is less than one-half that of urban areas. In those three regions alone, almost 2 billion people in rural areas are without access to adequate sanitation, and about 1 billion lack access to a reliable water supply. Some 1.3 billion in China and India alone lack adequate sanitation facilities.[14]

Figure 2: Share of Population with Access to Adequate Sanitation, 2002 (%)



Source: World Bank, 2005.

Unlike rural sanitation and water supply for which the percentage coverage has increased, the coverage for urban water supply appears to have decreased over the 1990s. The water supply and sanitation sector will face enormous challenges over the coming decades as the urban populations of developing countries are expected to increase dramatically. The African urban population is expected to more than double over the next 25 years, while that of Asia will almost double. The urban population of Latin America and the Caribbean is expected to increase by almost 50% over the same period. At the same time, rural areas also face the daunting task of meeting the existing large service gap.

To achieve the United Nation's Millennium Development Goals' (MDGs) 2015 targets for water and sanitation in the developing world, a further 2.2 billion people will need access to sanitation and 1.5 billion will need access to a water supply—this means providing water supply services to 280,000 people and sanitation facilities to 384,000 people every day for the next 15 years.[15]

Lack of drinking water and sanitation kills about 4,500 children a day. Meeting the MDG target of halving the proportion of people without access to safe drinking water and basic sanitation by 2015 would avert 470,000 deaths and result in an extra 320 million productive working days every year. Improving water and sanitation brings valuable social, economic, and environmental benefits. Depending on the region of the world, economic returns to investment in water may range from USD 3 to USD 34 for each dollar invested.[16]

> “Lack of drinking water and sanitation kills about 4,500 children a day.”

Over 90% of deaths from diarrheal diseases in the developing world today occur in children under five years old. Appropriate drinking water and sanitation services and better hygiene behavior is crucial in cutting child mortality. In sub-Saharan Africa and South Asia respectively, some 769,000 and 683,000 children under five years of age died annually from diarrheal diseases in 2000—2003. By contrast, in the developed regions, only 700 of the 57 million children under five years old succumbed to diarrheal disease annually[17] as most mothers and babies benefit from safe drinking water in quantities that facilitate hygiene while having access to better sanitation, adequate nutrition, and many other prerequisites to health.

Many children, mostly in Africa and Asia, are missing school because neither their homes nor schools have adequate drinking water and sanitation facilities. Disease, domestic chores (e.g., hauling water from distant sources), and lack of separate school latrines for girls and boys keep school attendance figures down. In 2002, more than 500 million school-age children lived in families without access to adequate sanitation, and 230 million were without a reliable water supply. Inadequate drinking water and sanitation services rob poor families of opportunities to improve their livelihoods.

> “Many children…are missing school because neither their homes nor schools have adequate drinking water and sanitation facilities.”

The elderly are more susceptible, and more likely, to die from diseases related to water, sanitation, and hygiene than other adults, especially in industrialized countries. More than one billion people will be 60 years or older by 2025.[18]

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[14] WHO and UNICEF, *Global*, op. cit.

[15] WHO and UNICEF, *Global*, op. cit.

[16] WHO and UNICEF, *Water*, op. cit.

[17] WHO and UNICEF, *Water*, op. cit.

[18] WHO and UNICEF, *Water*, op. cit.

Hundreds of millions of African, Asian, and Latin American families lose vital income from the lack of access to reliable drinking water and sanitation services. Globally, the World Health Organization (WHO) has estimated that productivity gains from diarrhea reduction by achieving the MDG drinking water and sanitation target will exceed USD 700 million a year. The income earned by those saved from premature death attributable to diarrhea adds another USD 3.6 billion a year. Healthcare services will also benefit, amounting to a saving of USD 7.3 billion a year. Meeting the MDG target would yield economic benefits close to USD 12 billion a year.

> “Meeting the MDG [drinking water and sanitation] target would yield economic benefits close to USD 12 billion a year.”

Such benefits would justify the USD 11.3 billion annual investments needed to provide appropriate drinking water and sanitation services. By far the biggest economic benefit comes from valuing the time saved when people who currently have inadequate services gain access to nearby water and sanitation facilities. Assuming that the average one hour per day saved by each household member can be used to earn the minimum daily wage, the saved time is worth USD 63 billion.[19]

[1.2] Population Projections and Resource Potential

Between 2000 and the year 2010, the population of developing countries is expected to grow by an amount greater than the total additional population served by the water and sanitation sector during the last decade. Consequently, internal and external financing of investments in the water sector will need to be significantly increased. As populations grow, communities already served by water and sanitation will place a greater strain on the water resources to supply their water needs and receive their waste. Supply and treatment systems will need to be expanded and upgraded to cope with the increased demands. In many cases, the resource potential of regions is already heavily exploited. In some cases, there is overexploitation, resulting in accelerated deterioration of both the quantity and quality of service that can be provided. Alternative methods for the collection, treatment, and disposal of wastewater or new water supply sources should be found.

Societies generally experience water shortages when annual renewable supplies become less than about 2,000 cubic meters per person. Water demands are outpacing supply in many developing countries, and water shortages are seriously affecting some industrialized nations as well. Former Soviet planners are trying to save the Aral Sea, one of the largest freshwater bodies, which has shrunk to 40% of its original area during the last few decades.[20] The western United States (especially California) experienced unprecedented shortages of fresh water for both urban areas and agriculture in the late 1980s and early 1990s. Rationing measures were introduced in 1991 by water suppliers in California.

Many developing countries have not developed policy instruments (i.e., either regulations or economic incentives). Both the opportunity costs of using water and costs of environmental degradation are generally ignored as excessive quantities of water are used and pollution is high. In the absence of a policy framework that takes account of such externalities, human activities both cause and are affected by closely related water quantity and quality problems.

[1.2.1] Costs of Conventional Water Supply

The increases in water resource development costs will decrease the effectiveness of available investment capital in terms of population reached or service level achieved. The real costs of meeting rising demand for all water users at an environmentally acceptable quality level is dramatically increasing throughout the developing world.[21] The three main manifestations include (a) the increase in long-term marginal costs of supply resulting from the added expenditure necessary to maintain supply and sanitation services at the existing quality level; (b) the incremental cost of upgrading and expanding existing supply and sanitation systems and bringing additional systems on line to satisfy the greater demands of growing communities; and (c) the increased per capita costs of supplying communities not yet covered due to more complex technical, social, and environmental factors affecting the exploitation of remaining water sources.

Clearly, the most convenient and cost-effective water resource sites have already been exploited, and what remains are the technically or environmentally more difficult, and hence more expensive, projects. Even in developing countries where water is not yet a scarce commodity, the technical solutions required to make the unexploited sources available are increasingly expensive.

The most dramatic examples of rising costs are in growing urban areas, where development of water resources cannot keep pace with the growth of demand.[22] Increasing unit costs and scarcity of funds implies that an increasing number of urban poor will continue to depend on unreliable public supplies or have to use surface and groundwater sources often contaminated by microbiological, organic, chemical, and heavy metal pollutants. As a result, health problems and mortality rates will increase, because the poor will have to spend a higher portion of their income to obtain water for basic needs or reduce their already meager consumption of water.

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[19] WHO and UNICEF, *Water*, op. cit.

[20] J. Perera, “A Sea Turns to Dust: Glasnost Brought the Plight of the Shrinking Aral Sea to the World's Attention, But with the Break-Up of the Soviet Union Rescue Plans Have Fallen Apart,” *New Scientist*, Issue 1896, October 1993.

[21] Munasinghe, *Water*, op. cit.

[22] Munasinghe, *Water*, op. cit.

Table 2 shows the average reported construction costs of different types of water supply facilities. The variations between regions are to some extent the result of differing water resource endowments, unit costs for construction, and levels of service offered. The figures are rough estimates and tend to vary widely because costs are significantly affected by factors such as population density and ease of access of water sources.

Table 2: Costs of Water Supply in Different Regions 1990 – 2000 (USD per Person Served)

Facility	Africa	Asia	Latin America and the Caribbean
House connection	102	92	144
Stand post	31	64	41
Borehole	23	17	55
Dug Well	21	22	45
Rainwater	49	34	36

Source: WHO and UNICEF, 2000.

[1.3] Poverty and Water

An increasing number of the poor—rural and urban consumers, rural producers, and agricultural workers—are coming to view access or entitlement to water as a more critical problem than access to food, primary health care, and education.

The typical urban household uses water for drinking and sanitation. Rural areas use water for a wide range of purposes, such as irrigation, domestic use, home gardens, trees and other permanent vegetation, livestock, fishing, harvesting of aquatic plants and animals, and a variety of other enterprises such as brick making.

> “Poor people depend on water in four key ways: as an input into production, to sustain livelihoods, for the maintenance of health and welfare, and to ensure ecosystem integrity.”

The quantity of water is as important as the quality in terms of its impact on human well-being.[23] Water quantity and quality are linked because water scarcity leads to declining water quality and pollution, which has an adverse impact on the poor. As water is withdrawn from agriculture, more attention must be paid to the management of irrigation systems, to water needs for domestic and health purposes, and to other consequences like the impact on the environment.

Ensuring that poor communities have access to water resources has become widely equated with ensuring that the basic needs of the poor are met, which in turn is interpreted as ensuring safe and affordable drinking water and sanitation, as is enshrined in the MDGs. Poor people depend on water in four key ways: as an input into production, to sustain livelihoods, for the maintenance of health and welfare, and to ensure ecosystem integrity.[24] There are also indirect effects.

Water as an Input into Production and Livelihoods

Water resources are vital inputs into productive activities. Agriculture is the basis of rural economies. About 35% of the world's populations depend on agriculture, ranging from 3% in Europe and America to 80% in Africa and 45 – 65% in Asia.[25] Agricultural viability is closely linked to reliable access to water, both from irrigation and rainfall. Improvements to existing irrigation systems have great potential for improving the livelihoods of the poor, provided that they have access to land and water.

Agricultural water has helped meet rapidly rising demand for food and contributed to the growth of farm profitability and poverty reduction as well as to regional development and environmental protection. The main challenge is to continue meeting these needs despite an increasingly constrained water resource base. The intense development of surface and groundwater irrigation has caused the remaining opportunities to harness new resources to be fewer and more expensive. In developing countries, the irrigated area more than doubled over the last 40 years.[26] However, the pace of irrigation development has slowed significantly. Most countries now face environmental and social constraints to expansion.

Actions such as rainwater harvesting, improved access to groundwater, and improvements to on-farm water management can bring dramatic and sustainable benefits to farmers who depend on rainfed agriculture. However, on their own, these measures are often inadequate. Watershed and forest protection at the community level must be integrated.

There are many smaller productive activities that depend on water as a key input, including fishing; tree and garden cultivation; livestock raising; small-scale manufacturing such as pottery, brick making, and tanning; and services such as laundering. Water is also vital for many types of manufacturing and other larger economic activities that provide employment for poor people, particularly in cities. The poor often rely on these production activities as their main livelihoods or to supplement their incomes and overcome their lack of assets such

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[23] Munasinghe, *Water*, op. cit.

[24] M. Munasinghe, "Sustainomics: Framework and Applications for Making Development More Sustainable," Munasinghe Institute for Development (MIND), Colombo, 2006; and M. Munasinghe, "Sustainable Water Resources Management and Planning (SWAMP)," Paper to the International Water Association Conference, Dubai, August 1994.

[25] FAOSTAT website, <http://faostat.fao.org/>

[26] World Bank, Re-engaging in Agricultural Water Management: Challenges and Options, World Bank, Washington, DC, 2006.

as land. Actions to sustain and expand these activities will often cost very little and can have significant and immediate benefits for the poor. Recognizing this potential requires a different approach to the provision of water supplies to households and communities by acknowledging its significance for production as well as consumption by the poor.

Water for Health and Hygiene

The health and welfare conditions of the poor, especially of vulnerable groups such as children, the elderly, and women in general, are closely connected to the availability of adequate, safe, and affordable water supplies. Worldwide there are an estimated 4 billion cases of diarrhea each year, causing 2.2 million deaths, mostly among children under the age of five.[27] Around 200 million people suffer from schistosomiasis, millions have been blinded by trachoma, and many more are affected by malaria, cholera, and other diseases where poor water management is a major causal factor. Toxins in groundwater such as arsenic and fluoride are an emerging threat in regions such as South Asia. These diseases have major consequences for poor people through their effects on nutrition, physical and mental development, the costs of health care, and the loss of productive potential. Improving the quality and quantity of water could significantly reduce the adverse health and welfare impacts of poor water supply and sanitation.

Role of Ecosystems in Supporting Livelihoods of the Poor

The flow and quality of water is critical for the viability of the ecosystems through which the poor gain access to the natural resources that are often the basis of their livelihoods. Even where water is not a direct input into production, other natural resources, such as forests, fish, or grazing lands that are contingent on the viability of ecosystem processes, depend on the flows of water. Although rarely monetized and often ignored, these goods are significant for the rural poor throughout the developing world.

Indirect Effects

It is widely recognized that there are tangible economic benefits to health and income that result from better access to clean water. However, water resource system planners in developing countries have overlooked other ways in which water may influence health and income among the urban poor. In such vulnerable groups, the high costs of water may further undermine health and labor productivity, both directly through its impact on nutrition and indirectly through its impact on housing size and quality as well as residential density, especially in urban slums. Failure to account for the full range of economic, social, and environmental benefits associated with improvements in water supply may lead to underestimation of returns to investment.

[1.3.1] Sustainable Livelihoods and Water

> “For many rural communities, access to natural resources such as water is vital to activities that are key parts of their livelihoods.”

Poverty is complex and multifaceted and reflects both the material and the nonmaterial conditions of people's lives; it has social, economic, and environmental dimensions. The concept of sustainable livelihoods is a flexible and dynamic approach that provides a basis for understanding the relationship between poor communities, their local environment, and external socioeconomic, environmental, and institutional forces. A livelihood comprises the capabilities; assets, including both material and social resources; and activities required for a means of living.[28] A livelihood is sustainable when the individual can cope with and recover from stresses and shocks while maintaining or enhancing capabilities and assets both now and in the future and not undermining the natural resources base.[28]

It is predominantly the poor of the world who depend directly on natural resources through cultivation, herding, collecting, or hunting for their livelihoods. Therefore, for such livelihoods to be sustainable, the natural resources base must be maintained.[30] For many rural communities, access to natural resources such as water is vital to activities that are key parts of their livelihoods. Water security suggests that people and communities have reliable and adequate access to water to meet their different needs, are able to take advantage of the opportunities that water resources present, are protected from water-related hazards, and have fair recourse when water conflicts arise.

[1.4] Water and Sustainable Development

[1.4.1] Basic Concepts of Sustainable Development

World decisionmakers are looking for new solutions to many critical problems including traditional development issues such as poverty as well as newer challenges like worsening environmental degradation. The sustainable development approach is becoming increasingly accepted as a potential response following the 1992 Earth Summit in Rio de Janeiro, the adoption by the United Nations of the 2000 Millennium Development Goals, and the 2002 World Summit on Sustainable Development in Johannesburg.[31] The sustainable

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[27] WHO and UNICEF, *Water*, op. cit.

[28] D. Carney (ed.), Sustainable Rural Livelihoods, Department for International Development, London, 1988.

[29] Ibid.

[30] J. K. Rennie and N. Singh, Participatory Research for Sustainable Livelihoods, International Institute for Sustainable Development, Winnipeg, 1996.

[31] World Commission on Environment and Development (WCED), *Our Common Future*, Oxford University Press, Oxford, UK, 1987; and UN, Agenda 21, United Nations, New York, 1993.

development concept encompasses three major points of view: economic, social, and environmental. Developing a practical framework to define, analyze and implement sustainable development, however, has been challenging,[32] but some efforts have been made to develop a comprehensive, balanced, and practical approach for "making development more sustainable."[33]

[1.4.2] Circular Interaction

Water resources and sustainable development interact in a circular manner. Different socioeconomic development paths, driven by the forces of population, economy, technology, and governance, give rise to various patterns of water use. The resultant changes in the hydrological cycle and water supply-demand balances in turn impose stresses on human socioeconomic and natural systems. Such impacts will ultimately have effects on development paths, thus completing the cycle. Different development paths will also have direct effects on natural systems in the form of non-water-related stresses such as environmental degradation. Thus, water resource issues are embedded in complex social, economic, and environmental systems that interact to shape prospects for sustainable development.

[1.4.3] Economic, Social, and Environmental Issues Arising from Inadequate Water Resources

Shortages of water, caused by both inadequate quantity and quality, pose a significant potential threat to the future economic well-being of large numbers of human beings, especially the poorest. In its simplest form, the economic efficiency viewpoint will seek to maximize the net benefits, or outputs of goods and services, from the use of water resources. Broadly speaking, this implies that scarce water must be allocated to the most productive uses. Thus, the efficient development of freshwater sources relies on least-cost investment, optimized water losses, and efficient operation. At the same time, on the demand side, the pricing of water at marginal cost is an important decentralized market mechanism by which efficient matching of multiple sources with multiple uses may be realized.

> **Economic:** “Shortages of water… pose a significant potential threat to the future economic well-being of large numbers of human beings.”

> **Social:** “Water is a basic need for survival, and, therefore, scarcities and water stress will also undermine social welfare and equity.”

> **Environmental:** “Water scarcity and declining quality will significantly perturb both terrestrial and marine critical global ecosystems.”

Water is a basic need for survival, and, therefore, scarcities and water stress will also undermine social welfare and equity. In particular, more attention needs to be paid to the vulnerability of social values and institutions that have evolved over many years to share water, because they are already stressed due to rapid technological changes. Especially within developing countries, erosion of social capital is undermining the basic glue that binds communities together (e.g., the rules and arrangements that align individual behavior with collective goals).[34] Inequity will undermine social cohesion and exacerbate conflicts over scarce water resources. Both intra- and intergenerational equity are likely to worsen in the water sector. Existing evidence clearly demonstrates that poorer nations and disadvantaged groups within nations are especially vulnerable to water-related disasters like droughts and floods.[35] Water scarcities are likely to worsen inequities due to the uneven distribution of the costs of damage, and such differential effects could occur both among and within countries. Developing country food production systems may prove vulnerable to a combination of water scarcities, climate change impacts, and accelerated globalization of commodity and financial markets, posing significant risks to the survival of billions of the poor.[36]

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[32] M. Munasinghe, Environmental Economics and Sustainable Development, Paper presented at the UN Earth Summit, Rio de Janeiro, 1992b; Environment Paper No.3, World Bank, Washington, DC, 1992b; and Munasinghe, *Water*, op cit.

[33] For example, M. Munasinghe, "The Sustainomics Trans-Disciplinary Framework for Making Development More Sustainable," International Journal of Sustainable Development, Vol. 4, No. 2, 2002, pp.6 – 54.

[34] T. Banuri et al., Sustainable Human Development: From Concept to Operation: A Guide for the Practitioner, UNDP, New York, 1994.

[35] C. Clarke and M. Munasinghe, "Economic Aspects of Disasters and Sustainable Development," in M. Munasinghe and C. Clarke (eds.), *Disaster Prevention for Sustainable Development*, International Decade of Natural Disaster Reduction (IDNDR) and World Bank, Washington, DC; and T. Banuri, "Human and Environmental Security," Policy Matters, Vol. 3, Autumn 1998.

[36] M. Munasinghe, *Sustainomics*, 2006, op. cit.

The environmental viewpoint draws attention to the fact that water resources are also physical systems. The need for an integrated approach is strengthened by recognizing the holistic nature of water resources (e.g., river basin, watershed, or aquifer) and the practical complications that arise when such a complete physical system cuts across national, administrative, or sectoral boundaries. Water scarcity and declining quality will significantly perturb both terrestrial and marine critical global ecosystems. Environmental sustainability will depend on several factors, including water availability (e.g., magnitude and frequency of shocks like floods and droughts), system vulnerability (e.g., extent of impact damage), and system resilience (i.e., ability to recover from impacts). More generally, changes in the global hydrological flows and balances will threaten the stability of a range of key, interlinked physical, ecological, and socioeconomic systems and subsystems.[37]

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[37] Intergovernmental Panel on *Climate Change, Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change*, R. T. Watson et al. (eds.), Cambridge University Press, London, 1996.

[2] case study of a simple water filtration method for cholera prevention in Bangladesh

[2.1] Background and Issues

Scarcity of safe drinking water remains a global problem and is expected to rise with population growth and environmental change. Given the challenges described in section 1, people in many parts of the world have made it a priority to develop practical and appropriate approaches to improve access to clean water and basic sanitation. The following case study highlights a simple, affordable sari cloth filter technology that was designed to remove cholera bacteria from water, thereby preventing outbreaks of this devastating waterborne disease. The technology does not incorporate nanotechnology, and is intended to illustrate the broad range of economic, social and environmental issues that confront individuals and organizations implementing projects in developing countries to improve access to clean water. The case study authors suggest that simple purification materials such as sari cloth, perhaps suitably treated or impregnated with nanotechnology-based materials described in section 3, could make the filters even more effective. The Bangladesh case study enables comparison to a project, featured in the South African Case Study (section 4) that utilizes nanotechnology.

> “Intervention methods should meet economic, social and environmental criteria (i.e., low cost, sociocultural acceptability, and environmental soundness). They [. . .] should be readily accessible to the public in developing countries.”

Waterborne diseases like cholera are a major threat in most developing countries. Although the availability of municipally treated water supplies has made a significant difference in curbing many waterborne diseases, there are still reports of major outbreaks caused by poor drinking water resulting from weak infrastructure and contamination of drinking water sources. Cholera and other diarrheal diseases are major killers, especially for children in developing countries. It is estimated that approximately 5.5 million cases of cholera are diagnosed annually. Population growth worldwide is largely responsible for the increased levels of pathogens in drinking water sources, and contaminated drinking water is a threat to public health unless appropriate interventions are taken locally, regionally, and globally.

In countries such as Bangladesh, tubewells that tap into groundwater are expected to provide safe drinking water. However, studies indicate that they fail to protect against gastrointestinal diseases. Underground water systems are increasingly vulnerable to both microbiological and heavy metal contamination such as arsenic. Arsenic contamination has been reported in countries such as Argentina, Chile, China, India, Mexico, Taiwan, and Thailand. As many as half the wells drilled in the late 1960s to counter Bangladesh's severe surface water pollution have been found to be contaminated with arsenic in amounts that exceed 50 ppb, with some concentrations higher in contaminated areas.

An important aspect of the microbiology of drinking water is the dormant state, or the survival strategy manifested by many waterborne pathogenic bacteria, called the viable but nonculturable (VBNC) phenomenon. In the VBNC state, bacteria remain viable, maintain virulence, but do not grow on conventional bacteriological culture media. These bacteria will, therefore, be left in the water if appropriate methods are not used for detection. Reevaluation of disinfectant protocols to treat water, including those employing chlorine, is necessary, especially when the effectiveness of municipal filtration and water purification systems is low, such as during severe floods.

Field research carried out at the University of Maryland and at the International Centre for Diarrheal Disease Research, Bangladesh, found that simple filtration can be useful in reducing cholera and other enteric diseases. Intervention methods need to meet economic, social and environmental criteria (i.e., low cost, sociocultural acceptability, and environmental soundness). They also should be readily accessible to the public in developing countries, especially after extreme weather conditions such as the monsoons. Although bottled water is a suitable alternative in developed countries, it is too expensive to be a viable option for people who suffer from waterborne diseases.

Unlike many other illnesses, waterborne diseases cannot be readily eradicated because many of the pathogens are naturally occurring in aquatic environments. However, intervention is possible by modifying social behavior to change the way water is used through general education, increased public awareness, and, most importantly, wide-spread initiatives to protect water from undesired contamination. Industrialization has led to problems of chemical pollution in many developing countries due to lack of resources and poor management. In addition, the emergence of pathogens resistant to chemicals used in water treatment is a concern for those responsible for clean, safe drinking water supplies.

The infectious agent causing cholera is a bacterium called *Vibrio cholerae*, which is transmitted through water. This bacterium occurs naturally in the aquatic environment. Studies revealed that *Vibrio cholerae,* if ingested, is likely to produce clinical cholera depending on the health of a given individual.[38] Bangladesh faces two types of water-related problems – during the monsoon, the floods, and during the dry season, severe aridity. During the summer months, occurrence of cholera vibrios increases in cholera endemic areas such as Bangladesh.[39] Severe flooding, which is common in Bangladesh, causes harsh conditions in some areas where even the barest necessities become difficult to obtain. Methods such as boiling water or treating water with chlorine that are used to purify water become more difficult to apply under such conditions. As a result, availability of safe drinking water becomes limited.

Boiling water prior to drinking helps kill other pathogens, including Cyclops (i.e., a planktonic stage of the guinea worm that causes dracunculiasis), guinea worm larvae, and other microorganisms. However, it is time-consuming and may be expensive in countries like Bangladesh where there is a shortage of fuelwood. In addition, boiling water is not the social norm in most rural villages of Africa[40] and Bangladesh. Filtering water at the time of collection and just before drinking has been successful in removing Cyclops. The Cyclops are removed using a nylon net, and filtration is now recommended as an effective method of preventing this life-threatening disease, at one time common in Africa.[41]

> “In Bangladesh, a majority of the population living in villages still depend on untreated surface water taken from ponds and rivers for household consumption”

In Bangladesh, a majority of the population living in villages still depend on untreated surface water taken from ponds and rivers for household consumption for reasons of taste and convenience, and based on the traditional belief that “quality” water is “natural,” it is not chemically treated. A study of cholera transmission among families and neighborhoods showed that those who used *V. cholerae* positive water for cooking, bathing, or washing but used *V. cholerae* negative water for drinking had the same rate of infection as those using *V. cholerae* positive water for drinking. This indicates the importance of using clean water for all household purposes and not only for drinking. Once a member of the family is contaminated, it is likely to spread among others through food or other methods of direct transmission.

During the monsoon season, vast areas in Bangladesh are submerged by floods, resulting in a few shallow hand-operated tubewells being available to the villagers. A large number of sanitary latrines also get flooded, causing a serious problem with hygiene and posing a direct threat of contamination by enteric bacteria including *V. cholerae*. Previous studies indicate that during late monsoons, phytoplankton blooms occur, followed by zooplankton blooms, to which vibrios are attached and multiply, increasing the number of *V. cholerae* in the natural water of the environment.[42] When consumption of surface water cannot be avoided, particularly during flooding or other natural disasters that occur every year in Bangladesh, a simple method that is effective in reducing the number of *V. cholerae* cells would be useful to curb the disease.

[2.2] Field Trial of Simple Sari Filtration Method

The experiment used a simple and inexpensive method that is acceptable to the community to sieve out plankton to which *V. cholerae* is attached, thereby reducing the cases of cholera. The method removes 99% of *V. cholerae* attached to the plankton, using four layers of sari cloth as the filter.[43]

Having used different types of material as filters from resources commonly found in the villages, it was found that old sari cloth worked better as a filter than new cloth. This was due to the fact that the threads of an old sari were frayed, producing a smaller mesh size compared to a new sari. Hence, four layers of old sari could produce a 30 mm mesh, which would be small enough to retain greater than 99% of copepods carrying *V. cholerae*, thereby reducing the pathogen cells up to two logarithms in water.

> …“four layers of old sari could produce a 30 Ìm mesh [filter]…”

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[38] R. Cash et al., “Response of Man to Infection with Vibrio Cholerae I. Clinical, Serologic, and Bacteriologic Responses to a Known Inoculum,” *Journal of Infectious Diseases*, Vol. 129, 1974, pp. 45 – 52.

[39] R. B. Sack et al., “A four-year study of the epidemiology of Vibrio cholerae in four rural areas of Bangladesh, *Journal of Infectious Diseases*, Vol. 187, 2003, pp. 96 – 101.

[40] WASH Campaign, *Orientation of Guinea Worm Disease: A Guide to Use in Pre-Service And In-Service Training*, USAID, Washington, DC, 1991.

[41] WASH, Ibid.

[42] R. Colwell and A. Huq, “Vibrios in the Environment: Viable but Non-Culturable Vibrio Cholerae,” in: I. K. Wachsmuth et al. (eds.), Vibrio Cholerae and Cholera: Molecular to Global Perspectives, ASM, Washington, D.C., 1994, pp. 117 – 133.

[43] Case study based on: UNDP-TWAS, *Examples of Successful Experiences in Providing Safe Drinking Water*, Volume 11, Section 1, South-South Cooperation Unit, UNDP, New York, and TWAS, Trieste, 2005.

Since the disease is dose dependent, filtration is a practical method for reducing cholera in areas where people must depend on untreated water, as no other methods are available or affordable. Therefore, a community-based study was targeted to under-privileged rural populations and sought to reduce cholera by directly involving the local community. Mothers of households were held responsible for implementation of the filtration system.

The method of sari filtration was tested in a field trial. Approximately 45,000 villagers were asked to participate in the trial, in three groups of 15,000 each. A first group was asked to use the devised sari filter, a second group was provided with nylon filters (as was used to control guinea worm disease in Africa), and a third group was used as a control, who continued their routine methods of water collection and were not given either a sari or nylon filter. The nylon and sari groups were educated on how to use their respective filters, while all three groups were informed about the importance of hygiene and personal health. In addition, posters that described the process and provided pictures of plankton were shown to individuals to emphasize the critical need for removing the plankton from the water. They were advised to use filtered water for all domestic and household purposes, including drinking, washing utensils and vegetables, and bathing. An extensive questionnaire was used both prior to and after the study to assess the knowledge gained by the participants concerning hygiene and the public health value of filtration as well as the willingness to participate in this program.

[2.3] Results

Four months after the system was introduced to the villages, it was found that 90% of the population accepted the sari filtration system into their daily lives and were willing to protect themselves from cholera. The field trial indicated that there was a significant reduction in the cases of cholera in the groups using the nylon and sari filtration systems. The group using the sari filtration method had 48% less cholera cases than the control group (i.e., cholera was reduced by about half). It should also be noted that the rates of cholera were relatively low during the years in which the field trials were conducted, compared to historic data in the same area of Matlab, Bangladesh.

> “It was clear that sari filtration contributed to bringing safer water into houses without any additional cost to the household…”

It was clear that sari filtration contributed to bringing safer water into houses without any additional cost to the household, resulting in significant health benefits to people who have very few other alternatives. It satisfied the economic, social, and environmental criteria indicated earlier (low cost, sociocultural acceptability, and environmental soundness), while being readily accessible to the public, especially after extreme weather conditions such as the monsoons. Although bottled water is another alternative for developing countries, it is expensive and thus will not provide a sustainable solution for the poor who suffer from waterborne diseases.

> …“several viullages have started using this method to filter household water.”

Following the successful field trials, several villages have started using this method to filter household water. It is important that villagers are properly informed through mass communication so that more people would use the sari filtration method, mainly because it costs very little, has significant economic benefits (i.e., through improved health), and is also environmentally and socially desirable.

[2.4] Simple Sustainable Development Assessment of Water Purification Methods

The conventional approach to evaluate the contribution of water projects to sustainable development would be to use cost-benefit analysis, where all project effects are valued in monetary terms. However, in many cases, environmental and social effects cannot be easily valued; other techniques like multi-criteria analysis (MCA) need to be applied. This approach is also attractive to decision makers who prefer to consider a range of feasible alternatives as opposed to one "best" solution. MCA allows for the appraisal of alternatives with differing objectives and varied costs and benefits, which are often assessed in differing units of measurement. In brief, MCA examines alternative ways of meeting multiple objectives, which cannot be measured in terms of a single criterion (i.e., monetary values).

As described in annex 1, the sustainable water resources management and planning (SWAMP) approach provides an integrated framework for coordination of water resource investment planning and pricing, policy analysis and formulation, as well as policy implementation and management. The framework takes into account all three aspects of sustainable development (i.e., economic, social, and environmental) and offers a tool to decisionmakers to evaluate trade-offs between various policy options. Options that lead to improvements in all three indices are referred to as "win-win" options. Once "win-win" options are realized, policymakers are able to make trade-offs among other available options.

The figure within annex 1 shows how the sari-based water purification method may be assessed quite simply within the SWAMP framework using MCA. The analysis indicates a "win-win" future option with the simplified sari filtration technique, in which all three indices economic efficiency, social equity, and environmental protection improve. Economic losses due to sickness are reduced overall; social gains accrue to the rural poor, especially women and children; and the environment benefits from reduced pollution of water sources.

[2.5] Potential for Nanotechnology-Based Purification

The success of the simple sari purification method suggests that similar materials, perhaps suitably treated or impregnated with nanotechnology-based methods, could filter more effectively and thereby increase the health benefits. Villagers who used the sari method are likely to be more easily persuaded to adopt a superior filtration technology, provided it is cheap, readily available, and convenient to use. From the perspective of making development more sustainable, the health, social, and environmental benefits could be increased, but economic costs will also rise unless appropriate, low-cost nanotechnology could be developed.

Some of the nanotechnology-based purification methods described in section 3 are worth considering if one wishes to go beyond the simple sari-based technique. One of the disadvantages of the conventional water treatment method is that it cannot remove dissolved salts and some soluble inorganic and organic substances. Nanomembranes and nanoclays are an inexpensive, mobile, and cleanable system that will purify, detoxify, and desalinate water. Nanosensors could detect contaminants and pathogens, thereby helping to improve health, maintain a safe food and water supply, and facilitate the use of otherwise unusable water sources. Nanoelectrocatalysts might be used for anodic decomposition of organic pollutants and the removal of salts and heavy metals from liquids, allowing the use of heavily polluted and heavily salinated water for drinking, sanitation, and irrigation. The main advantages of the membrane process are that chemicals are not added for the water treatment, relatively little energy is required, it is easy to operate and maintain, and substances can be selectively removed.

> “The success of the simple sari purification method suggests that similar materials, perhaps suitably treated or impregnated with nanotechnology-based methods, could filter more effectively and thereby increase the health benefits.”

[3] nanotechnology & water

As described in detail in section 1, scarcity of water, in terms of both quantity and quality, poses a significant threat to the current and future well-being of people worldwide, but especially to people in developing countries. Sustainable water management is a critical aspect of addressing poverty, equity, and related issues. Science and technology has a role to play in contributing to the development of new methods, tools, and techniques to solve specific water quality and quantity problems. As demonstrated in section 2, projects that meet economic, social, and environmental criteria can contribute to sustainable management of water resources and improve access to clean water for poor people in developing countries. The case study in section 2 illustrates the issues that any project, whether it uses conventional or nanotechnology-based water treatment devices, must consider. This section provides an overview of water treatment devices that incorporate nanotechnology; some of these are already on the market while others are still in development. The section then explores potential environmental and health risks, risk governance issues, and socio-economic issues regarding the potential use of nanotechnology to improve access to clean water and basic sanitation.

> “Several publications in the past two years have described the possible role nanotechnology can play in providing clean water in developing countries…”

Several publications in the past two years have described the possible role nanotechnology can play in providing clean water in developing countries by offering new and better technological solutions for removing pollutants from contaminated water.[44] People interested in the role of science and technology for meeting the needs of poor people in developing countries have suggested that applications of nanotechnology aimed at more effectively removing contaminants from water could potentially solve problems that have proven challenging to solve with conventional technologies.[45] However, people are also concerned about the potential health and environmental risks and potential socioeconomic issues associated with the use of nanotechnology in developing countries.[46]

In exploring whether and how nanotechnology could be applied responsibly to offer new and better solutions, this paper describes a range of available products and promising research that apply nanotechnology to provide clean water. In particular, this section and section 4 describe nanofiltration membrane technologies used to clean water. The section then describes socioeconomic issues and potential environmental and human health risks of using nanotechnology to clean water.

Different countries and regions face different environmental, social, and economic conditions and have different needs with regard to water use and water quality. The case studies in sections 3 and 4 demonstrate the differences in access to technology, field conditions, and the types of technologies that may be appropriate in different circumstances. The following sections describe various options nanotechnology may offer. In order to relate specific examples of technologies to their potential role to provide clean water in developing countries, the authors use specific standards, conditions, and situations found in South Africa as their benchmark. These sections should not be construed as prescribing general or specific formulas as solutions to water quality problems.

[3.1] Water Pollution and Nanofiltration

Water that does not meet drinking water standards should be treated to ensure that the health of the consumer or community is not compromised through exposure to toxic pollutants. Polluted water is often treated by conventional or pressure-driven membrane processes to make it comply with drinking water standards. The conventional water treatment process consists of several stages. These include pre-treatment, coagulation, flocculation, sedimentation, disinfection, aeration, and filtration. The pre-treatment stage removes suspended solids. Coagulation and flocculation are carried out to precipitate dissolved impurities through sedimentation. The water is then filtered to remove any suspended particles. One of the disadvantages of the conventional water treatment method is that it cannot remove dissolved salts and some soluble inorganic and organic substances.[47]

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[44] For instance, UN Millennium Project 2005, “Innovation: Applying Knowledge in Development,” Task Force on Science, Technology, and Innovation, 2005, <http://www.unmillenniumproject.org/ reports/reports2.htm>; F. Salamanca-Buentello et al., “Nanotechnology and the Developing World,” PLoS Medicine, 2005, <http://medicine.plosjournals.org/perlserv/?request=get-document&doi=10.1371/journal.pmed.0020097>; NanoWater, <http://www.nanowater.org/>; and B. Wootliff, “Canadian Invites the World to Pool its Resources on Clean Water,” Small Times, November 18, 2003, <http://www.smalltimes.com/document_display.cfm?document_id=6959>.

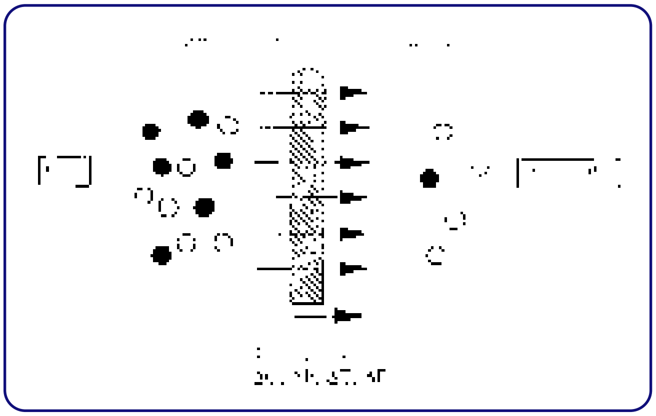
[45] P. A. Singer, “Think Small,” Canada.com, November 9, 2005.

[46] Reuters, “Industry Urged to Be Open about Nano Testing Methods,” May 4, 2006, <http://abcnews.go.com/Technology/print?id=1922633>; and ETC Group, “Nanotech Product Recall Underscores Need for Nanotech Moratorium: Is the Magic Gone?” April 7, 2006, <http://www.etcgroup.org/article.asp?newsid=559>.

[47] W. J. Voortman and C. D. Reddy, Package Water Treatment Plant Selection, Part 1, Guidelines, WRC Report No. 450/1/97; and Filtration Industry Analyst, Desalination – A Snapshot, 2005, pp. 3 – 7.

Pressure-driven membrane technology is an ideal method for the treatment of water to any desired quality. The integral part of the technology is the membrane. The membrane is a barrier that separates two homogenous phases. It allows some solutes to pass through but rejects the permeation of others. It achieves the separation of solutes of a fluid mixture when a driving force is applied. The force could be a pressure difference (Δp), concentration gradient (Δc), temperature difference (ΔT), or electrical potential difference (ΔE). The basic principle of operation is illustrated in Figure 3. Phases 1 and 2 are generally the feed water and the product water or permeate, respectively. The basis of separation is that each membrane has unique characteristics for the selective permeation and rejection of different solutes.[48]

Figure 3: Schematic Representation of a Two-Phase System Separated by a Membrane



Source: Mulder, 1997.[49]

There are four pressure-driven membrane processes. These are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). These processes may be distinguished by pore size, transport mechanism, applied pressure, and range of applications. The pore sizes for MF, UF, NF, and RO are respectively 0.05 10 µm, 1 – 100 nm, < 2 nm, and < 2 nm. The pore sizes decrease from MF to RO membranes. The pore sizes correspond to the size of molecules that are retained by the membrane. NF and RO membranes are the most widely used membrane processes in water treatment. MF and UF membranes are generally used in pre-treatment. The main advantages of the membrane process for water treatment is that it does not require chemicals, requires relatively low energy, and is easy to operate and maintain.[50]

> “Nanofiltration membrane technology is widely applied for removal of dissolved salts from salty water, removal of micro pollutants, water softening, and wastewater treatment.”

Nanofiltration (NF) membrane technology is widely applied for removal of dissolved salts (i.e., desalination) from salty (i.e., brackish) water, removal of micro pollutants (e.g., arsenic and cadmium), water softening (i.e., removal of calcium and magnesium ions), and wastewater treatment. RO membranes are also used for the desalination of brackish water, ocean, and seawater. RO and NF water treatment plants typically consist of two types of treatment stages in series. These are the pre-treatment and membrane systems. The pre-treatment system removes particulate matter, in particular, suspended solids. The membrane removes some soluble substances and minute substances that were not rejected by the pre-treatment system. RO treatment plants reject all soluble and minutely insoluble substances but water.

> “Nanofiltration membranes… selectively reject substances… [which] enables the retention of nutrients present in water that are required for the normal functioning of the body.”

NF membranes, on the contrary, selectively reject substances. The characteristic selectivity of NF has advantages in comparison to RO because it enables the retention of nutrients present in water that are required for the normal functioning of the body. For example, calcium ions are necessary for the healthy development of bones.[51]

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[49] B. Nicolaisen, "Developments in Membrane Technology for Water Treatment," *Desalination*, Vol. 153, 2003, pp. 1 – 3, 355 – 360; and M. Mulder, *Basic Principles of Membrane Technology*, 2nd ed., Kluwer Academic Publishers, Dordrecht, 1997.

[49] Mulder, op. cit.

[50] Mulder, op. cit.; and J. L. Moitsheki, "Evaluation of the Performance of Nanofiltration Membranes in Detrimental Ion Rejection and To Monitor Fouling and Membranes with Their Subsequent Chemical Cleaning," master's thesis, Potchefstroom University, Potchefstroom, South Africa, 2003; and A. Sonune and R. Ghate, "Developments in Wastewater Treatment Methods," *Desalination*, Vol. 167, 2004, pp. 55 – 63.

[51] Filtration Industry Analyst, op. cit.; and Mulder, op. cit.; and Moitsheki, op. cit.

[3.2] Examples of Nanofiltration for Water Purification and Detoxification

3.2.1 Nanofiltration Membranes

Researchers are using nanomaterials (e.g., carbon nanotubes, alumina fibers) to build structures that have controlled shapes, density, and dimensions for specific filtration applications. For instance, researchers have developed and tested cylindrical membranes with pores tiny enough to filter out the smallest organisms.

Rensselaer Polytechnic Institute in the U.S. and Banaras Hindu University[52] in India devised a simple method to produce carbon nanotube filters that efficiently remove micro- to nanoscale contaminants from water. Made entirely of carbon nanotubes, the filters are easily manufactured using a novel method for controlling the cylindrical geometry of the structure. Carbon nanotube filters offer a level of precision suitable for different applications as they can remove 25-nanometer-sized polio viruses from water as well as larger pathogens such as E. coli and Staphylococcus aureus bacteria. The nanotube based water filters were found to filter bacteria and viruses and were more resilient and reusable than conventional membrane filters. The filters were reusable and could be cleaned by heating the nanotube filter or purging. Nano-engineered membranes allowed water to flow through the membrane faster than through conventional filters due to the straighter membranes than conventional filters.[53]

Argonide[54] in the United States, using grant money from the U.S. National Aeronautics and Space Administration, has developed a filter comprising oxidized aluminum nanofibers on a glass fiber substrate. These alumina fibers are positively charged, which enables them to filter bio-organisms such as bacteria and viruses from the water flow. Even though the pores in this filter are relatively large, the end result is extremely effective because the process provides a much higher flow rate than traditional membranes. The filter retains up to 99.999% of viruses, is currently in production, and can be used to clean water by applying muscle force with no extra energy needed, ideal for rural contexts.

SolmeteX,[55] based in the United States, uses its experience and expertise in water chemistry, surface chemistry, and separation science to develop and manufacture heavy metal binding resins that remove metals and metal complexes, including mercury, arsenic, cyanide, and cadmium, from water. The company continues to investigate further areas where their targeted, upstream approach to toxic component removal can also be efficiently and costeffectively applied.

Filmtec, a U.S. subsidiary of Dow Chemical Company, supplies nanofiltration elements that are used to purify public drinking water supplies. These elements are used to treat municipal water supplies where salts such as calcium and magnesium must be removed. Filmtec's nanofiltration membrane offers high rejection of pesticides and other dissolved organics, low salt rejection, low energy consumption, and stable performance after repetitive cleaning.[56]

Table 3: Specific Examples of Nanofiltration Membrane Technologies

Organization	Country	Type of Technology	Link
Rensselaer Polytechnic Institute	United States	Devised a simple method to produce carbon nanotube filters that efficiently remove micro-to-nano-scale contaminants from water.	http://www.rpi.edu/
Banaras Hindu University	India	Devised a simple method to produce carbon nanotube filters that efficiently remove micro-to-nano-scale contaminants from water.	http://www.bhu.ac.in/
Argonide	United States	Developed a filter comprising oxidized aluminum nanofibers on a glass fiber substrate.	http://www.argonide.com/
SolmeteX	United States	Develop and manufacture heavy metal binding resins that remove metals and metal complexes, including mercury, arsenic, cyanide, and cadmium from water.	http://www.solmetex.com/
Filmtec Corporation[57]	United States	Nanomembrane filtration technologies	http://www.dow.com/liquidseps/prod/prd_film.htm http://www.dow.com/liquidseps/index.htm
North West University, Potchefstroom	South Africa	Nanomembrane filtration technologies	http://www.puk.ac.za/fakulteite/natuur/scb/index_e.html
University of Stellenbosch, Institute for Polymer Science	South Africa	Nanomembrane filtration technologies	http://academic.sun.ac.za/polymer/

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[52] Efficient Filters Produced from Carbon Nanotubes through Rensselaer Polytechnic Institute – Banaras Hindu University Collaborative Research, 2004, <http://news.rpi.edu/update.do?artcenterkey=435>.

[53] A. Srivastava et al., "Carbon Nanotube Filters," *Nature Materials* 3, 2004, pp. 610–614.

[54] Argonide, <http://www.argonide.com/>.

[55] Solmetex, <http://www.solmetex.com/>.

[56] Filmtec, <http://formembranes.com/DeFilmT4.pdf>, <http://www.dow.com/liquidseps/index.htm>.

[57] Filmtec Corporation is a subsidiary of Dow Chemical Company. CHC is a local distributor of Filmtec products in South Africa.

[3.2.2] Attapulgite Clays, Nanoporous Zeolites, and Nanoporous Polymers

Other source materials for nanofilters include zeolites, attapulgite clays, and nanoporous polymers. Zeolites, attapulgite clays, and polymers have been used for many years to purify water. Recent improvements in scientists' ability to see and manipulate on the nanoscale allow for greater precision in designing these materials, for instance, allowing much greater control over pore size of membranes.[58]

Attapulgite clays are naturally occurring materials, which are locally available in many places around the world. A study looking at the use of attapulgite clay membranes to filter waste water from a milk factory in Algeria showed that using the locally available clay in the filtration process offered an economical and effective method for reducing the amount of whey and other organic matter to make the wastewater safe to drink.[59]

Zeolites are microporous crystalline solids with well-defined structures. Generally they contain silicon, aluminium, and oxygen in their framework and cations, water, and/or other molecules within their pores. Many occur naturally as minerals and are extensively mined in many parts of the world. Others are synthetic and are made commercially for specific uses or produced by research scientists trying to understand more about their chemistry. Zeolites can be used to separate harmful organics from water and to remove heavy metal ions from water.[60]

Researchers at Los Alamos National Laboratory have developed a new class of nanoporous polymeric materials that can be used to reduce the concentration of common organic contaminants in water to parts-per-trillion levels.[61] These organic nanoporous polymers with narrow pore-size distribution (0.7 – 1.2 nm) have been synthesized using cyclodextrins as basic building blocks. The researchers say that the binding between organic contaminants and the nanoporous polymer is 100,000 times greater than the binding between organic contaminants and activated carbon, which is commonly used in wastewater treatment. These materials can be used for the purification of municipal water supplies or for recycling and reuse of industrial wastewater.

Table 4: Specific Examples of Nanoporous Polymers

Organization	**Country**	**Type of Technology**	**Link**
Los Alamos National Laboratory	United States	Developed a new class of nanoporous polymeric materials that can be used to reduce the concentration of common organic contaminants in water to parts-per-trillion levels.	http://www.lanl.gov/

[3.2.3] Desalination

Desalination is the removal of dissolved salts from raw or untreated water by either thermal or membrane processes. A thermal process uses heat to evaporate water, which is then collected by condensation. In a membrane process, pressure is applied to force the raw water through a membrane that retains the dissolved salts.[62] Reverse osmosis (RO) membranes can retain all the salt, whereas other membrane processes, such as nanofiltration (NF), selectively retain some salts. Desalination is carried out for various reasons, including limited freshwater, increasing demand, global warming, regulation, cost effectiveness, and politics.

A reverse osmosis (RO) desalination plant consists of the following sequence of stages: feed water intake system, pre-treatment facility, high-pressure feed pumps, RO membrane, desalinated water conditioning system. A pressure of 40 – 80 bars is required for the permeation of water through the RO membrane for the desalination of seawater. Two membrane sheets are glued together and spirally wound around a perforated central tube. The product water exits through this tube.[63]

Nanotechnology is used in Israel for the desalination of saline waters. The Grand Water Research Institute of the Israel Institute of Technology[64] is working with corporate and other partners to treat salt water and create fresh sources for drinking water and irrigation. They are using reverse osmosis whereby pressure is applied to salt water, forcing the fluid through a very fine membrane resulting in (virtually) pure water.

> “The major setback of desalination is that production costs are very high. … It is expected that nanotechnology… will drive down the costs of desalination.”

A major impediment to wider adoption of desalination technology is high production costs. A third of the costs are required for supplying the energy that forces the water through the membrane. Although significant advancements in technology have extended membrane life

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[58] Cientifica, "Nanoporous Materials," 2003, <http://www.cientifica.com/>.

[59] K. Khider et al., "Purification of Water Effluent from a Milk Factory by Ultrafiltration Using Algerian Clay Support," Desalination, 167, 2004, pp. 147 – 151, <http://www.desline. com/articoli/5700.pdf>.

[60] British Zeolite Association, <http://www.bza.org/>.

[61] M. C. Roco, et al. (eds.), "Visions for Nanotechnology Research and Development in the Next Decade," Interagency Working Group on Nanoscience, Engineering, and Technology, Loyola College, Maryland, September 1999, Section 10, "Nanoscale Processes in the Environment," pp. 143 – 153 and Los Alamos National Laboratory, "Nanoporous Polymers for Water Purification," <http://www-emtd.lanl.gov/TD/Remediation/NanoPorousPolymer.html>.

[62] Filtration Industry Analyst, op. cit.

[63] Filtration Industry Analyst, op. cit.

[64] The Stephen and Nancy Grand Water Research Institute, <http://gwri.technion.ac.il>.

while lowering energy requirements, overall energy consumption remains extremely high. Desalination costs about USD 1 per m^3 of salt water and USD 0.60 per m^3 of brackish water. It is expected that nanotechnology will contribute to improvements in membrane technology that will drive down the costs of desalination. For instance, the Long Beach Water Department has reduced the overall energy requirement (by 20 to 30 percent) of seawater desalination using a relatively low-pressure two-staged nanofiltration process. This unique process is now being tested on a larger scale.[65]

Table 5: Specific Examples of Desalination Using Nanotechnology

Organization	**Country**	**Type of Technology**	**Link**
The Stephen and Nancy Grand Water Research Institute	Israel	Using reverse osmosis whereby pressure is applied to salt water, forcing fluid through a very fine membrane resulting in virtually pure water.	http://gwri.technion.ac.il/
Long Beach Water Department	United States	Reduced overall energy requirement of seawater desalination using a relatively low pressure two staged nano filtration process.	http://www.waterindustry.org/New%20Projects/desal-20.htm

[3.2.4] Suitability of the Nanomembrane Technologies for Developing Countries

There are merits and demerits of nanomembrane technologies (e.g., nanofiltration and reverse osmosis) over conventional filtration technologies. The conventional sand filter does not retain some microbes and dissolved salts (e.g., arsenate). Nanofiltration (NF) and reverse osmosis (RO) membranes remove all multivalent ions and bacteria.[66] The conventional carbon filter, biological sand, and biological carbon filters do not remove some bacteria and dissolved salts (e.g., calcium). Calcium is readily removed by the nanomembrane processes. However, NF membranes have a low rejection coefficient (R) for monovalent ions. Thus, they are not well suited for the removal of nitrate and fluoride ions from water,[67] which could be an advantage in cases where fluoride ion levels are suitable for the healthy development of teeth.

The only additional equipment required for NF membrane filtration, compared to conventional filtration, is cartridge filters. These serve as a pre-treatment for the removal of particulate matter before membrane filtration. Their cost is insignificant. One of the setbacks of nanomembrane technology is cost. The cost of a full-scale conventional filtration plant is about 70% of a nanomembrane plant. The durability of a nanomembrane plant is comparable to that of a conventional filter plant and is determined by the nanomembrane whose life span ranges between five and six years.[68] The life span can be further prolonged by using an effective pre-treatment.[69]

Nanomembrane filtration technologies are suitable for developing countries. Nanomembrane plants can be built as portable units, which can be assembled in the major urban centers and then transported to the outlying areas (i.e., rural and peri-urban) where they are needed. By building the plants as portable units, the initial capital required for the construction can be lowered.

Nanofiltration technologies are easily accessible in developing countries, for instance, the European and U.S. companies that manufacture these nanomembranes have subsidiary companies in South Africa. The local agent of Filmtec, a subsidiary of Dow Chemical Company, is CHC, which has offices in Cape Town and Johannesburg. Countries in the Southern African Development Community (SADC), who may not be able to access nanomembranes in their respective countries, can order them from South Africa. Nanomembranes are also manufactured by various companies in South Africa, including the University of Stellenbosch Institute for Polymer Science and North West University, Potchefstroom.

[3.3] Other Approaches Using Nanotechnologies to Clean Water

Various nanomaterials and nanotechnologies, other than nanofiltration (described above), are in development; these technologies may also enable the more efficient and effective removal of pollutants from water. While the assessment of nanomembrane filtration technology is informed by the authors' experience with this technology, their experience with the relatively new technologies in the following sections is limited. Some of the technologies are still at the developmental stages, and information about their future performance, especially in comparison to conventional technologies, is not yet available.

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[65] Water Industry News, "Long Beach Water Department Wins $3 Million California Grant for Innovative Seawater Desalination Project," April 12, 2005, <http://www.waterindustry.org/New%20Projects/desal-20.htm>.

[66] Mulder, op. cit.; and Moitsheki, op. cit.

[67] Mulder, op. cit.

[68] Filtration Industry Analyst, op. cit.

[69] Voortman, op. cit.; and Filtration Industry Analyst, op cit.

[3.3.1] Nanoparticles for the Catalytic Degradation of Water Pollutants

A catalyst is a substance that promotes the chemical reaction of other materials without becoming permanently involved in the reaction. Researchers are exploring how nanocatalysts such as titanium dioxide (TiO_2) and iron nanoparticles can be used to degrade organic pollutants and remove salts and heavy metals from liquids. People expect that nanoelectrocatalysts will enable the use of heavily polluted and heavily salinated water for drinking, sanitation, and irrigation.[70] Using catalytic particles either dispersed homogeneously in solution or deposited onto membrane structures could chemically degrade pollutants instead of simply moving them somewhere else. Catalytic treatment of polluted water could be specifically targeted to degradation of chemicals for which existing technologies are inefficient or cost prohibitive.

Researchers are experimenting with, for example, a method using nanoscale zero-valent iron as a catalyst to remove arsenic from groundwater.[71] Other researchers are developing an iron-storage protein that consists of a native nano-size iron oxide core that may serve as catalysts in (photo)chemical degradation processes of common contaminants.

Several companies are developing applications that are already on the market or will be soon. For instance, U.S.-based Inframat Corporation is developing a material composed of a highly porous nanofibrous structure that can be used to remove arsenic from drinking water by combining a nanofibrous MnO_2 oxidative process with a granular ferric hydroxide adsorptive process.[72] The technology supposedly circumvents the limitations of today's active-site nanoparticulate materials that have a strong tendency to form agglomerates, which limit the permeability of the reactive constituents into and through the agglomerated mass. Another company, EnvironmentalCare from Hong Kong, has developed a nano-photocatalytic oxidation technology for the removal of bacteria and pollutants from water.[73] It uses nano-coated TiO_2 filters that trigger a chemical process, which converts harmful pollutants into the harmless end products of carbon dioxide and water. In photocatalysis, water passing through a nanomaterial is also subjected to ultraviolet light, leading to the destruction of contaminants.

> “Catalytic treatment of polluted water could be specifically targeted to degradation of chemicals for which existing technologies are inefficient or cost prohibitive.”

Another example of potentially promising research is provided by researchers in the United States at the Universities of Illinois and Pittsburgh and Yeshiva University who are exploring the use of nanocatalysts to reduce pollution of oxidized contaminants (e.g., nitrates). Presently, nitrate in drinking water is either not removed or it is removed using ion exchange resins. The former presents health risks, and the latter is expensive because waste streams must still be treated when the resins are regenerated. Nitrate is a stable and highly soluble ion with a low potential for co-precipitation or adsorption so that removal of nitrates using conventional water treatment is difficult. This research focuses on identifying the most promising catalysts (e.g., bimetallic metal catalysts such as Pd-Cu) to use for the reduction of nitrate and other oxidized compounds and to gain fundamental understanding of the reactivity and selectivity of these new catalytic materials.[74]

Researchers at Rice University in the United States are exploring nanocatalysts to remove tri-cholorethylene and organic aromatic contaminants, mainly pesticides, from groundwater.[75] The researchers suggest that although each system requires a different catalyst and overall remediation strategy, nanoscale engineering of materials permits the design of more efficient systems. For instance, the researchers have developed a new way to produce high surface area (> 250 m2/gm) nanocrystalline titania, which under UV illumination is capable of photo-oxidizing a variety of molecules. Additionally, ongoing work on the environmental implications of fullerenes, particularly C_{60}, led these researchers to hypothesize that the oxygen radical production capabilities of nanoscale C_{60} aggregates in water could be leveraged for degradation of contaminants.

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[70] “Forging Ahead: Technological Innovation and the Millennium Development Goals,” Task Force on Science, Technology, and Innovation, UN Millennium Project, November 8, 2004, <http://www.cid.harvard.edu/cidtech/TF10Edit11-8.pdf>.

[71] U.S. Department of Commerce, “U.S. EPA Workshop on Nanotechnology for Site Remediation,” Washington, DC, October 20 – 21, 2005, <http://es.epa.gov/ncer/publications/workshop/ pdf/10_20_05_nanosummary.pdf>; and L. McDowall, “Degradation of Toxic Chemicals by Zero-Valent Metal Nanoparticles – A Literature Review,” Commonwealth of Australia, 2005, <http://www.dsto.defence.gov.au/publications/4278/DSTO-GD-0446.pdf>.

[72] Inframat, “Description of Nanofibrous MnO2 Bird's-Nest Superstructure Catalyst,” <http://www.inframat.com/cat2.htm>.

[73] Nano-Fotocide, <http://www.fotocide.com/index.html>.

[74] H. Xu et al., “Structural Changes of Bimetallic PdX/Cu (1-X) Nanocatalysts Developed for Nitrate Reduction of Drinking Water,” *Materials. Research Society Symposium Proceedings*, Vol. 876E, 2005, <http://pubweb. bnl.gov/users/frenkel/www/MRS/MRS-2005-1.pdf>.

[75] Center for Biological and Environmental Nanotechnology, “Nanocatalysts for Remediation of Environmental Pollutants,” <http://cohesion.rice.edu/centersandinst/cben/research.cfm?doc_id=5099>.

Table 6: Specific Examples of Nanoparticles for Catalytic Degradation of Water Pollutants

Organization	Country	Type of Technology	Link
Inframat Corporation	United States	Developing a material composed of highly porous nanfibrous structure that can be used to remove arsenic from drinking water by combining a nanofibrous MnO_2 oxidative process with a granular ferric hydroxide adsorptive process	http://www.inframat.com/
EnvironmentalCare	Hong Kong	Developed a nano-photocatalytic oxidation technology for the removal of bacteria and pollutants from water	http://www.environmentalcare. com.hk/
University of Illinois, University of Pittsburgh, Yeshiva University	United States	Exploring the use of nanocatalysts to reduce pollution of oxidized contaminants (e.g. nitrates)	http://www.uillinois.edu/, http://www.pitt.edu/, http://www.yu.edu/, http://pubweb.bnl.gov/users/frenkel/www/MRS/MRS-2005-1.pdf
Rice University	United States	Exploring nanocatalysts to remove trichloroethylene and organic aromatic contaminants from groundwater	http://cohesion.rice.edu/centersandinst/cben/research.cfm?doc_id=5099

[3.3.2] Magnetic Nanoparticles for Water Treatment and Remediation

Magnetic nanoparticles are being developed to adsorb metals and organic compounds. When coated with different compounds that have a selective affinity for diverse contaminating substances, magnetic nanoparticles could be used to remove pollutants, including arsenic, from water. This class of technologies seems especially suited for decomposing organic pollutants and removing salts and heavy metals from liquids.[76] Worldwide, arsenic poisoning is a huge public health disaster in many developing nations, as described elsewhere in this article. New technologies that can target and remove heavy metal contaminants, such as arsenic, from drinking water are desperately needed.

> …“magnetic nanoparticles… seem especially suited for decomposing organic pollutants and removing salts and heavy metals from liquids.”

Brazilian researchers have developed superparamagnetic nanoparticles that, coated with polymers, can be spread over a wide area in dustlike form; these modified nanomagnets would readily bind to the pollutant and could then be recovered with a magnetic pump.[77] Because of the size of the nanoparticles and their high affinity for the contaminating agents, almost 100 percent of the pollutant would be removed. The magnetic nanoparticles and the polluting agents would be separated, allowing for the reuse of the magnetic nanoparticles and for the recycling of the pollutants.

Researchers at Rice University are developing magnetite nanocrystals[78] for arsenic removal from water.[79] According to the researchers, iron mineral surfaces show preferential sorption of arsenic species, and these magnetic particles can be removed from water via magnetic separations. The researchers at Rice University developed a strategy

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[76] Singer, op. cit.

[77] P. A. Singer et al., "Harnessing Nanotechnology to Improve Global Equity," *Issues in Science and Technology*, Summer 2005, <http://www.issues.org/21.4/singer.html>.

[78] Magnetite is defined by Merriam Webster's Dictionary as a "black isometric mineral of the spinel group that is an oxide of iron and an important iron ore."

[79] Center for Biological and Environmental Nanotechnology, "Sorption of Contaminants onto Engineered Nanomaterials," <http://cohesion.rice.edu/centersandinst/cben/research. cfm?doc_id=5100>.

for generating monodisperse magnetite, which provides for good size control in the 15 – 20 nm diameter range, which is the size range most useful for magnetic separations. Surface chemical control over these materials is essential as they are produced in organic solvents. This research confirmed that nanoscale magnetite is as effective as bulk iron minerals in its sorption of arsenic. In fact, not only is its sorption capacity higher but the material once associated with the nanoparticles is difficult to remove. Taken together these results indicate that magnetite nanoparticles are very effective adsorbents for arsenic, especially at low pH, and their irreversible sorption provides an efficient storage sink for collection of the waste.

The researchers at Rice University applied oxidative cleavage of hydrophobic capping groups on magnetite to yield water-soluble materials with high yield in a single step. Other methods have been described to develop magnetic nanomaterials, including physical methods of melting and ball-milling the desired material[80] and synthesizing nanoparticles by means of the arc-discharge method.[81]

Table 7: Specific Examples of Magnetic Nanoparticles for Water Treatment and Remediation

Organization	**Country**	**Type of Technology**	**Link**
Rice University	United States	Developing magnetite nanocrystals for arsenic removal from groundwater	http://cohesion.rice.edu/centersandinst/cben/research.cfm?doc_id=5100

[3.3.3] Nanosensors for the Detection of Contaminants and Pathogens

Nanosensors for the detection of contaminants and pathogens can improve health, maintain a safe food and water supply, and allow for the use of otherwise unusable water sources. Conventional water quality studies rely on a combination of on-site and laboratory analysis, which requires trained staff to take water samples and access to a nearby laboratory to conduct chemical and biological analysis. Nanosensors can detect single cells or even atoms, making them far more sensitive than counterparts with larger components. Detection technology for water purification would allow people to more quickly find out what the contaminants are, without having to send samples to laboratories for testing.

> “New sensor technology…is expected to lead to small, portable, and highly accurate sensors to detect chemical and biochemical parameters.”

New sensor technology combined with micro- and nanofabrication technology is expected to lead to small, portable, and highly accurate sensors to detect chemical and biochemical parameters. The potential impact of nanotechnology on the sensor market is huge. For example, the nanosensor market in the United States is currently estimated at USD 190 million and is expected to grow at an average annual growth rate of 26% to reach USD 592 million by 2009.[82]

Several organizations are developing systems that provide real-time detection of waterborne viruses and particles. These systems may be commercialized soon. Following are three examples of projects that apply nanotechnology to improve the functionality of sensors. For instance, other research is experimenting with single- and double-walled carbon nanotubes that can detect chemicals in water.[83]

The European Committee funded project BioFinger in developing a portable, versatile, and low-cost molecular detection tool. BioFinger is developing a handheld device that incorporates nano- and microcantilevers on a microchip. The microchip is disposable after each use, allowing it to be reconfigured with new on-chip cantilevers configured to detect different molecules. Each disposable chip is expected to cost around 8 Euros.[84] The system could be used to analyze chemicals and bacteria in water. The BioFinger project was due to begin testing its system in 2005 amid expectations for a commercial product to be available on the market within two to three years.

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[80] M. Bettge et al., "Physically Synthesized Ni-Cu Nanoparticles for Magnetic Hyperthermia," BioMagnetic Research and Technology, Vol. 2, No. 4, May 8, 2004, <http://www. biomagres.com/content/2/1/4>.

[81] R. Fernández-Pacheco et al., "Highly Magnetic Silica-Coated Iron Nanoparticles Prepared by the Arc-Discharge Method," Nanotechnology, Vol. 17, February 7, 2006, pp. 1188 – 1192, <http://www.iop.org/EJ/abstract/0957-4484/17/5/004>.

[82] "Nanosensors Market," III-Vs Review, October 21, 2004, <http://www.three-fives.com/business_ market_news/october04_mkt_bus_news/211004Nanosensors_market.htm>.

[83] H. Verdala et al., "Surface Modification of Carbon Nanotubes Using Poly (Vinyl Alcohol) for Sensor Applications," International Latin American and Caribbean Conference for Engineering and Technology, Miami, June 2 – 4, 2004, <http://www.laccei.org/proceedings2004/ FinalPapers/ET_062.pdf>.

[84] BioFinger, <http://www.biofinger.org/>; and Information Society Technologies, "Portable Molecular Detection Tool to Revolutionise Medical Diagnosis," <http://istresults. cordis.lu/index.cfm/Section/news/Tpl/article/BrowsingType/Features/ID/77729/highlights/biofinger>.

Researchers from the University of Buffalo in the United States, with funding from the National Science Foundation, are developing a handheld sensor that can detect the presence of toxins potentially used as agents in biological warfare.[85] The sensor will be composed of three components—an LED (i.e., light-emitting diode), a xerogel-based sensor array, and a complementary metal-oxide semiconductor detector, commonly used in miniature digital cameras. In experiments using this sensing system, the researchers successfully designed a prototype that detected the presence of oxygen. According to the researchers, the sensors can be constructed to detect many different toxins or to detect the same toxin in different ways as a fail-safe. When light from the sensors is imaged onto the face of the CMOS detector, an electrical signal is produced, which can be read by a personal digital assistant, mobile phone, or similar handheld device.

A Binghamton University chemist has been awarded a three-year grant from the U.S. Environmental Protection Agency to develop advanced nanosensors for continuous monitoring of heavy metals in drinking water and industrial effluent.[86] The researchers have already developed a prototype nanosensor that can concentrate and trap lead particles ten times smaller than a human hair. The researchers intend to develop a one-square centimeter prototype nanoreactor that is capable of detection and remediation of lead, cadmium, arsenic, chromium 6, and copper.

Table 8: Specific Examples of Nanosensors for the Detection of Contaminants and Pathogens

Organization	Country	Type of Technology	Link
BioFinger	Europe	Developing a portable molecular detection tool	http://www.biofinger.org/
University of Buffalo	United States	Developing a handheld sensor that can detect the presence of toxins potentially used as agents in biological warfare.	http://www.buffalo.edu/
University of Maryland	United States	Found that simple filtration can be useful in reducing cholera and other enteric diseases	http://www.umd.edu/

[3.4] Human Health and Environmental Risks

Although advances in nanotechnology may bring benefits to society, many people also raise concerns about potential environmental and health risks of nanomaterials. They feel that inadequate safety research is being conducted and fear that hazards may go undetected in the absence of thorough risk studies.[87]

> “If nanotechnology is to be used appropriately in developing countries to address water issues, it is critical that people in developing countries assess the potential risks as well as the opportunities.”

Several fundamental aspects of nanotechnology cause concern that the risks associated with nanomaterials may not be the same as the risks associated with the bulk versions of the same materials. For instance, as a particle decreases in size, a larger proportion of atoms is found at the surface as compared to the inside. Thus, nanoparticles have a much larger surface area per unit mass compared with larger particles. Also, as the size of matter is reduced to tens of nanometers or less, quantum effects can begin to play a role, and these can change optical, magnetic, and electrical properties of materials. Since growth and catalytic chemical reactions occur at surfaces, a given mass of nanomaterials will be more reactive than the same mass of materials made up of larger particles. These properties might have negative health and environmental impacts and may result in greater toxicity of nanomaterials.[88]

If nanotechnology is to be used appropriately in developing countries to address water issues, it is critical that people in developing countries assess the potential risks as well as the opportunities. Unfortunately, very little is known about engineered nanomaterials and how they interact with cells and biological organisms. The study of nanoparticles' toxicity is complicated by the fact that they are highly heterogeneous. Not only are they exclusively engineered to specification but in many cases nanoscale materials will alter in physical size upon interaction with aqueous systems. Furthermore, the surface coating of nanoparticles can be altered to completely change the material's toxicity. For example, changing the surface features of the material can change a hydrophobic particle into a hydrophilic one.[89]

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[85] J. Della Contrada, "UB Researchers Developing Sensors to Detect Agents Used in Biological Warfare," *UB Reporter*, December 4, 2003, <http://www.buffalo.edu/reporter/vol35/ vol35n14/ articles/TitusBiosensors.html>.

[86] S. E. Barker, "A Featherweight Solution for a Weighty Problem: BU Chemist Wins $351K EPA Grant to Develop Nanoreactor to Detect, Trap Heavy Metals in Water," *discover-e*, 2003, <http://research.binghamton.edu/Discovere/june2003/TopStories/OSadik.htm>.

[87] E. Harrell and I. Johnston, "Health Fears as Hi-Tech Science Hits the Shops," *The Scotsman*, May 3, 2006, <http://news.scotsman.com/index.cfm?id=658762006>.

[88] I. Bruske-Hohlfeld, et al., "Do Nanoparticles Interfere with Human Health?" GAIA, Vol. 14, No. 1, 2005, pp. 21–23, <http://www.oekom.de/gaia>.

[89] L. Goldman and C. Coussens (eds.), "Implications of Nanotechnology for Environmental Health Research," National Academy of Sciences Roundtable on Environmental Health Sciences, Research and Medicine, Environmental Health Research, 2005 <http://www.iom.edu/CMS/3793/4897/26111.aspx>.

After reviewing the current literature on human health and environmental risks of nanotechnology, it appears that only a limited number of studies on the potential toxicity of specific nanoscale materials have been published. Some papers seem to indicate that there may be unique risks associated with nanoscale materials (e.g., ability of some nanoscale materials to pass through the blood-brain barrier) and are cause for concern. However, other research indicates that there may be ways to reduce the potential toxicity of nanoscale materials, for instance, by altering the surface coating of these materials.

For the purpose of this paper, there is yet insufficient information to characterize the materials used in the specific technologies described in sections 2.2 and 2.3 and also the risks associated with these specific nanomaterials to adequately describe the potential risks associated with the specific examples of types of technologies described in sections 2.2 and 2.3 of this paper. The following sections provide an overview of key issues in order to inform further discussions on the types of issues that should be considered in assessing the role of nanotechnology in addressing the need for clean water in developing countries.

[3.4.1] Human Health Effects of Nanoscale Materials

Health and toxicity have been and still are highly contentious issues in regard to nanotechnologies. Initial research results demonstrate the complexity of assessing the potential risks associated with nanomaterials.

> People could be exposed to nanoparticles through inhalation, ingestion, skin uptake, and injection of nanoscale materials.

People could be exposed to nanoparticles through inhalation, ingestion, skin uptake, and injection of nanoscale materials. In order to assess the safety of engineered nanostructures and nanodevices, research is needed about the effects of these materials on biological organisms. To date, there are very few publications on the safety evaluation of nanomaterials. An editorial in the journal *Toxicological Sciences* states that "in a search of the published literature as of 1 August 2005, fewer than ten papers on safety evaluations of nanomaterials were found."[90] A review of some of these publications gives a sense of the complexity of assessing the potential risks of nanoscale materials.

> In order to assess the safety of engineered nanostructures and nanodevices, research is needed about the effects of these materials on biological organisms.

Research on the Impacts of Carbon Nanotubes and Other Nanomaterials

Several laboratory experiments have been conducted with carbon nanotubes, a class of nanoscale materials used in various forms of water filtration. A recent study on functionalized water soluble carbon nanotubes intravenously administered to mice shows that the tubes were still intact when excreted through urine.[91] Another study, which intratrachially instilled carbon nanotubes in mice, found that the carbon nanotubes used in the study were more toxic than carbon black and can be more toxic than quartz.[92] Yet another study showed that the cytotoxicity of carbon nanotubes could be reduced by changing the surface coating of the carbon nanotubes.[93] Research with superparamagnetic iron oxide nanoparticles also showed that cytotoxicity can be reduced by modifying the surface coating of these nanomaterials.[94]

While coating or covalently modifying the outer surfaces of nanomaterials may eliminate the toxicity of particles under laboratory conditions, questions remain about whether under environmental conditions the nanomaterials will still be benign. A recent study demonstrated that if surface-modified C60 materials were irradiated with ultraviolet radiation cytotoxicity returns.[95] Research with cadmium selenide (CdSe) quantum dots suggests that air exposure and nanoparticle dose are also important for cytotoxic effects, although those studies were not conducted with carbon nanotubes.[96] Since these studies were conducted under laboratory conditions, they indicate that even though nanomaterials with certain coatings may be safe under laboratory conditions, it may be necessary to test these compounds under environmental conditions.

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[90] M. P. Holsapple and L. D. Lehman-McKeeman, "Forum Series: Research Strategies for Safety Evaluation of Nanomaterials," *Toxicological Sciences*, Vol. 87, No. 2, 2005, p. 315.

[91] K. Kostarelos et al., "Tissue Biodistribution and Blood Clearance Rates of Intravenously Administered Carbon Nanotube Radiotracers," Proceedings of the National Academy of Sciences, Vol. 103, No. 9, February, 21, 2006, pp. 3357 – 3362, <http://dx.doi.org/10.1073/pnas.0509009103>.

[92] C. W. Lam et al., "Pulmonary Toxicity of Singe-Wall Carbon Nanotubes in Mice 7 and 90 Days after Intratrachial Instillation," *Toxicological Sciences*, Vol. 77, 2004, pp.126 – 134.

[93] C. M. Sayes et al., "Functionalization Density Dependence of Single-Walled Carbon Nanotubes Cytotoxicity in Vitro," *Toxicology Letters*, Vol. 161, 2006, pp.135 – 142.

[94] A. K. Guptaa and M. Gupta, "Cytotoxicity suppression and cellular uptake enhancement of surface modified magnetic nanoparticles," *Biomaterials*, Vol. 26, 2005, pp. 1565 – 1573.

[95] F. Rancan et al., "Protection against UVB irradiation by natural filters extracted from lichens," *Journal of Photochemistry and Photobiology*, Vol. Biology 68, 2002, pp.133 – 139.

[96] A. M. Drefus et al., "Probing the Cytotoxicity of Semiconductor Quantum Dots," *Nano Letters*, Vol. 4, 2004, pp. 11 – 18.

> “Although research on the impacts of nanomaterials is limited, risk experts are looking to the results of…studies with incidental and natural nanoscale particles and…studies with airborne ultrafine particles as the basis for the expanding field of nanotoxicology.”

Although research on the impacts of nanomaterials is limited, risk experts are looking to the results of older biokinetic studies with incidental[97] and natural[98] nanoscale particles and newer epidemiologic and toxicological studies with airborne ultrafine particles as the basis for the expanding field of nanotoxicology. Experts have identified some emerging concepts of nanotoxicology from the results of these earlier studies.[99] When inhaled, specific sizes of nanoscale particles are efficiently deposited by diffusional mechanisms in all regions of the respiratory tract. The small size facilitates uptake into cells and into the blood and lymph circulation to reach potentially sensitive target sites such as bone marrow, lymph nodes, spleen, and heart. Access to the central nervous system and ganglia has also been observed. Nanoscale particles penetrating the skin distribute via uptake into lymphatic channels. The greater surface area per mass compared with larger-sized particles of the same chemistry renders nanoscale particles more active biologically. This activity includes a potential for inflammatory and pro-oxidant, but also anti-oxidant, activity, which can explain early findings showing mixed results in terms of toxicity of nanoscale particles to environmentally relevant species.

Numerous epidemiological studies conducted worldwide have demonstrated consistent associations between short-term elevations in ultrafine particulate matter (e.g., diesel particles, asbestos) and increases in daily cardiovascular morbidity and mortality. There is much evidence from environmental epidemiologic studies on the adverse health effects of ultrafine particles, and there is a long-standing experience with occupational diseases associated with exposure to respirable dust. However, it is completely unknown whether or not this knowledge is relevant for manmade nanomaterials, and many researchers feel that this existing body of research is a starting point for assessing the health effects of nanomaterials.[100]

[3.4.2] Environmental Effects of Nanoscale Materials

Nanomaterials may affect aquatic or terrestrial organisms differently than larger particles of the same materials. As noted above, assessing nanomaterial toxicity is extremely complex and multifactorial and is potentially influenced by a variety of physicochemical properties such as size and shape and surface properties such as charge, area, and reactivity. Furthermore, use of nanomaterials in the environment may result in novel by-products or degradates that also may pose risks.

Based on analogy to physical-chemical properties of larger molecules of the same material, it may be possible to estimate the tendency of nanomaterials to cross cell membranes and bioaccumulate. However, current studies have been limited to a very small number of nanomaterials and target organisms. To date, very few ecotoxicity studies with nanomaterials have been conducted. Studies have been conducted on a limited number of nanoscale materials and in a limited number of aquatic species. There have been no chronic or full lifecycle studies reported.

> …“few ecotoxicity studies with nanomaterials have been conducted. Studies have been conducted on a limited number of nanoscale materials and in a limited number of aquatic species. There have been no chronic or full lifecycle studies reported.”

The few studies that have been reported include studies[101] of the effects of fullerenes in the brain of juvenile largemouth bass. The study concluded that C60 fullerenes induce oxidative stress, based on the researchers' observations that (a) there was a trend for reduced lipid peroxidation in the liver and gill, (b) significant lipid peroxidation was found in brains, and (c) a metabolic enzyme was marginally depleted in the gill. However, no concentration-response relationship was evident.

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[97] Incidental nanomaterials can be defined as materials with a structure between approximately 1 nm and 100 nm that are produced as a by-product of a process. For instance, welding fume and diesel emission particulates would be considered incidental nanomaterials.

[98] Natural nanomaterials can be defined as materials with a structure between approximately 1 nm and 100 nm that are a result of natural processes. Some particles arising from volcanic emissions, sea spray, and atmospheric gas-to-particle conversion would be considered natural nanomaterials.

[99] G. Oberdörster, et al., "Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles," *Environmental Health Perspectives*, Vol. 113, No. 7, July 2005.

[100] Bruske-Hohlfeld, op. cit.; and Goldman and Coussens, op. cit.

[101] E. Oberdorster, "Toxicity of NC60 Fullerenes to Two Aquatic Species: Daphnia and Largemouth Bass," American Chemical Society, Anaheim, CA, March 27 – April 2004; and E. Oberdorster, "Manufactured Nanomaterial (Fullerenes, C60) Induce Oxidative Stress in the Brain of Juvenile Largemouth Bass," *Environmental Health Perspectives*, Vol. 12, No. 10, 2004, pp.1058 – 1062.

Researchers[102] tested titanium dioxide (TiO2) and uncoated C60 fullerenes in a standard 48-hour acute toxicity test. These authors found that both nanomaterials were somewhat toxic to the Daphnia magna with fullerenes exhibiting a slightly greater toxicity than TiO2. However, the way the particles were prepared impacted toxicity, with filtering of the water to remove larger particles enhancing apparent toxicity. Large particles of titanium dioxide (i.e., the kind found in sunblock, paint, and toothpaste) did not cause toxicity. Additionally, in behavior tests with filtered fullerenes, Daphnia exhibited behavioral responses, with juveniles showing an apparent inability to swim down from the surface and adults demonstrating sporadic swimming and disorientation. [103]

Other researchers investigated the phytotoxicity of alumina nanoparticles.[104] The study looked at the impact of nanoparticles with different surface characteristics on the degree of root elongation inhibition caused by the particles. The researchers found that the surface characteristics of the particles appear to play an important role in the phytotoxicity of alumina nanoparticles.

[3.4.3] Risk Research and Governance

Current funding worldwide for research and development of nanoscience and nanotechnology is significantly greater than research on related environmental and human health issues. In the United States, environmental and industry representatives alike have urged that federal spending on environmental, health, and safety research of nanotechnology should be USD 100 million to USD 200 million a year, or about 10% to 20% of the government's USD 1.1 billion nanotechnology development budget for 2006. Estimates of actual government investments in health and safety research are closer to 4% of overall annual investments in nanotechnology. An incomplete inventory of environment, health, and safety research in several key countries (United States, Canada, United Kingdom, European Union, Japan, Taiwan, Germany, Denmark) shows over 200 relevant research projects accounting for over USD 38 million.[105] With the resources available, researchers need to examine the technology so that the science is in a better position to answer basic questions about health and environmental risks. Many researchers have suggested that a research agenda should be developed to ensure that the right questions are being asked and that the research effort is coordinated. The program should be flexible to respond to emerging challenges as they occur. [106]

Table 9: Examples of Existing Research on Health and Environmental Impacts

Organization	**Title**	**Reference**	**Link**
I. Bruske-Hohlfeld, et al.	Do Nanoparticles Interfere with Human Health?	*GAIA*, Vol. 14, No. 1, 2005, pp. 21–23,	www.oekom.de/gaia
A. M. Drefus et al.	Probing the Cytotoxicity of Semiconductor Quantum Dots	*Nano Letters*, Vol. 4, 2004, pp. 11 – 18	
L. Goldman and C. Coussens (eds.)	Implications of Nanotechnology for Environmental Health Research	National Academy of Sciences Roundtable on Environmental Health Sciences, Research and Medicine, Environmental Health Research, 2005	http://www.iom.edu/CMS/3793/4897/26111.aspx
A. K. Guptaa and M. Gupta	Cytotoxicity suppression and cellular uptake enhancement of surface modified magnetic nanoparticles	*Biomaterials*, Vol. 26, 2005, pp. 1565 – 1573	
E. Harrell and I. Johnston	Health Fears as Hi-Tech Science Hits the Shops	*The Scotsman*, May 3, 2006	http://news.scotsman.com/index.cfm?id=658762006
M. P. Holsapple and L. D. Lehman-McKeeman	Forum Series: Research Strategies for Safety Evaluation of Nanomaterials	*Toxicological Sciences*, Vol. 87, No. 2, 2005, p. 315.	
R. H. Hurt et al.	Toxicology of Carbon Nanomaterials: Status, Trends, and Perspectives on the Special Issue	*Carbon*, Vol. 44, Issue 6 , pp. 1028 – 1033, 2006	

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[102] S. B. Lovern and R. D. Klaper, "Daphnia Magna Mortality When Exposed to Titanium Dioxide and Fullerene (C60) Nanoparticles," *Environmental Toxicolology and Chemistry*, Vol. 25, No. 4, 2006, pp. 1132 – 1137.

[103] "Nanotechnology White Paper," U.S. Environmental Protection Agency, December 2, 2005, <http://www.epa.gov/osa/pdfs/EPA_nanotechnology_white_paper_external_review_draft_12-02-2005.pdf>.

[104] L. Yang and D. J. Watts, "Particle Surface Characteristics May Play an Important Role in Phytotoxicity of Alumina Nanoparticles," *Toxicology Letters*, vol. 158, 2005, pp. 122 – 132.

[105] "Inventory of Nanotechnology Health and Environmental Implications," Project on Emerging Nanotechnologies, <http://www.nanotechproject.org/index.php?id=18>.

[106] "Strategic Plan for NIOSH Nanotechnology Research: Filling the Knowledge Gaps," National Institute for Occupational Safety and Health, 2005, <http://www.cdc.gov/niosh/topics/nanotech/strat_plan.html>.

Table 9: Examples of Existing Research on Health and Environmental Impacts (cont)

Organization	**Title**	**Reference**	**Link**
K. Kostarelos et al.	Tissue Biodistribution and Blood Clearance Rates of Intravenously Administered Carbon Nanotube Radiotracers	*Proceedings of the National Academy of Sciences*, Vol. 103, No. 9, February, 21, 2006, pp. 3357 – 3362	http://dx.doi.org/10.1073/pnas.0509009103
C. W. Lam et al.	Pulmonary Toxicity of Singe-Wall Carbon Nanotubes in Mice 7 and 90 Days after Intratrachial Instillation	*Toxicological Sciences*, Vol. 77, 2004, pp.126 – 134	
S. B. Lovern and R. D. Klaper	Daphnia Magna Mortality When Exposed to Titanium Dioxide and Fullerene (C60) Nanoparticles	*Environmental Toxicology and Chemistry*, Vol. 25, No. 4, 2006, pp. 1132 – 1137	
A. Nel et al.	Toxic Potential of Materials at the Nanolevel	*Science*, Vol. 311, No. 576, 2006, pp. 622 – 627	
National Institute for Occupational Safety and Health	Strategic Plan for NIOSH Nanotechnology Research: Filling the Knowledge Gaps	National Institute for Occupational Safety and Health, 2005	http://www.cdc.gov/niosh/topics/nanotech/strat_plan.html
E. Oberdorster	Toxicity of NC60 Fullerenes to Two Aquatic Species: Daphnia and Largemouth Bass	American Chemical Society, Anaheim, CA, March 27 – April 2004	
E. Oberdorster	Manufactured Nanomaterial (Fullerenes, C60) Induce Oxidative Stress in the Brain of Juvenile Largemouth Bass	*Environmental Health Perspectives*, Vol. 12, No. 10, 2004, pp.1058 – 1062	
G. Oberdörster, et al.	Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles	*Environmental Health Perspectives*, Vol. 113, No. 7, July 2005	
G. Oberdorster, et al.	Principles for Characterizing the Potential Human Health Effects from Exposure to Nanomaterials: Elements of a Screening Strategy	*Particle and Fibre Toxicology*, Vol. 2, No. 8, 2005	http://www.particleandfibretoxicology.com/content/2/1/8
F. Rancan et al.	Protection against UVB irradiation by natural filters extracted from lichens	*Journal of Photochemistry and Photobiology*, Vol. Biology 68, 2002, pp.133 – 139	
Royal Society and Royal Academy of Engineering	Nanoscience and nanotechnologies: opportunities and uncertainties	Royal Society and Royal Academy of Engineering, 2003	http://www.nanotec.org.uk/finalReport.htm
C. M. Sayes, et al.	Functionalization Density Dependence of Single-Walled Carbon Nanotubes Cytotoxicity in Vitro	*Toxicology Letters*, Vol. 161, 2006, pp.135 – 142	
U.S. Environmental Protection Agency	Nanotechnology White Paper	U.S. Environmental Protection Agency, December 2, 2005	http://www.epa.gov/osa/pdfs/EPA_nanotechnology_white_paper_external_review_draft_12-02-2005.pdf
L. Yang and D. J. Watts	Particle Surface Characteristics May Play an Important Role in Phytotoxicity of Alumina Nanoparticles	*Toxicology Letters*, vol. 158, 2005, pp. 122 – 132	

In order to assist in the development of a coordinated research program to assess potential risks of nanoscale materials, the International Risk Governance Council has identified four overlapping generations of new nanotechnology products that have the potential for development between 2000 and 2020: passive nanostructures, active nanostructures, systems of nanosystems, and heterogeneous molecular nanosystems. Each generation of products is marked by the creation of commercial prototypes using systematic control of the respective phenomena and manufacturing processing. The rudimentary capabilities of nanotechnology today for systematic control and manufacture at the nanoscale are expected to evolve significantly in complexity and degree of integration by 2020. Most of the nanotechnologies for water purification available today are probably in the first, and possibly in the second, generation of nanotechnology products.[107]

The main deficit of risk governance for the first generation of passive nanostructures (e.g., nanoparticles, coatings, nanostructured materials) is the relatively low level of knowledge of the new properties and functions on toxicity and bioaccumulation and limited understanding of the nanomaterials' exposure rates. The main deficit for the new generations of nanoproducts, (including active nanodevices, nano-bio applications, and nanosystems is the uncertain/unknown evolution of the technology and human effects (e.g., health, changes at birth, brain understanding and cognitive issues, and human evolution) as well as a framework through which policies can address such uncertainties.

To fill the gap in knowledge about nanomaterials, common frameworks for risk research, risk assessment, and risk management, several organizations are developing applicable frameworks and protocols.[108] Some of the critical issues and research needs that are relevant in the developing field of nanotoxicology[109] include the following:

- ☐ Need for detailed materials characterization;
- ☐ Need for realistic exposure scenarios;
- ☐ Need for methods to track nanomaterials in biological experiments;
- ☐ Need for sensitive detection methods to determine dose metrics; and
- ☐ Need to identify key indicators of toxicity.

There is also a need to define a systematic and disciplined process that can be used to identify, manage, and reduce potential health, safety, and environmental risks of nanoscale materials across all lifecycle stages. DuPont and Environmental Defense are developing such a framework, which will be pilot-tested on specific nanoscale materials or applications of commercial interest to DuPont.[110]

Further complicating the research of environmental and human health issues is the lack of a nomenclature for the field. Currently, the science is based on the size of nanoparticles but does not take into account the basic chemical structure, such as titanium or carbon, or the surface coating of the nanoparticles.[111] Several efforts are now under way to develop a common nomenclature, including projects by the Nanotechnology Technical Committee of the International Organization for Standardization[112] and the ASTM International Committee E56 on Nanotechnology.[113]

Table 10: Examples of Existing Risk Governance Initiatives

Organization / Publication	Title	Link
International Risk Governance Council	Nanotechnology Project	http://www.irgc.org/irgc/projects/nanotechnology/
International Organization for Standardization	ISO Launches Work on Nanotechnology Standards	http://www.iso.org/iso/en/commcentre/pressreleases/ archives/2005/ Ref980.html
ASTM	ASTM, Technical Committees	http://www.astm.org/cgi-bin/SoftCart.exe/COMMIT/COMMITTEE/E56.htm?L+mystore+gxyx8351+1115426305
European Commission, Health & Consumer Protection Directorate-General, Scientific Committee on Emerging and Newly Identified Health Risks	Opinion on the Appropriateness of Existing Methodologies to Assess the Potential Risks Associated with Engineered and Adventitious Products of Nanotechnologies	http://ec.europa.eu/health/ph_risk/committees/04_scenihr/docs/scenihr_o_003b.pdf
Environmental Defense and DuPont	Environmental Defense and DuPont: Global Nanotechnology Standards of Care Partnership	http://www.environmentaldefense.org/article.cfm?contentID=4821
Azonano.com	DuPont, Environmental Defense Create Framework for Nanotechnology	http://www.azonano.com/news.asp?newsID=1536

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[107] International Risk Governance Council, "Nanotechnology Project," <http://www.irgc.org/irgc/ projects/nanotechnology/>.

[108] Ibid.; and Azonano.com, "DuPont, Environmental Defense Create Framework for Nanotechnology," October 12, 2005, <http://www.azonano.com/news.asp?newsID=1536>.

[109] R. H. Hurt et al., "Toxicology of Carbon Nanomaterials: Status, Trends, and Perspectives on the Special Issue," Carbon, Vol. 44, Issue 6 , pp. 1028 – 1033, 2006; A. Nel et al., "Toxic Potential of Materials at the Nanolevel," Science, Vol. 311, No. 576, 2006, pp. 622 – 627; G. Oberdorster et al. "Principles for Characterizing the Potential Human Health Effects from Exposure to Nanomaterials: Elements of a Screening Strategy," Particle and Fibre Toxicology, Vol. 2, No. 8, 2005, <http://www.particleandfibretoxicology.com/content/2/1/8>.

[110] Environmental Defense, "Environmental Defense and DuPont: Global Nanotechnology Standards of Care Partnership," October 11, 2005, <http://www.environmentaldefense.org/ article.cfm?contentID=4821>.

[111] Goldman and Coussens, op. cit.

[112] International Organization for Standardization, "ISO Launches Work on Nanotechnology Standards," November 16, 2005, <http://www.iso.org/iso/en/commcentre/pressreleases/ archives/2005/ Ref980.html>.

[113] ASTM, Technical Committees, <http://www.astm.org/cgi-bin/SoftCart.exe/COMMIT/COMMITTEE/E56.htm?L+mystore+gxyx8351+1115426305>.

[3.4.4] Interventions to Assist Developing Countries in Assessing and Managing Risk

Nanomaterials used in existing nanofiltration membranes are generally in an embedded form matrix. Some people suggest that the risks associated with these materials are likely to be limited as long as they are embedded in a matrix.[114] However, a life cycle assessment of these materials should consider potential exposure routes during production, use, and discharge of the product that contains the nanomaterials. Relatively little information is available about potential risks associated with specific nanoscale materials. Matters are complicated further because many technologies are still in development, and many new (forms of) nanoscale materials are being developed. The challenges related to assessing and managing the potential risks of nanoscale materials are relevant to people in both developed and developing countries. Therefore, it is imperative that information about potential risks and risk management approaches is shared widely and that instructions and training for handling nanomaterials and managing risks are developed and made available.

Table 11: Examples of Publicly Accessible Databases of Risk Related Information

Organization / Publication	Title	Description	Link
International Council on Nanotechnology	ICON Environmental, Health and Safety (EHS) database	The ICON EHS database contains summaries (abstracts) and citations for research papers related to the EHS implications of nanoscale materials. This database was developed initially by Dr. Tim Borges and Ms. LeeAnn Wilson at Oak Ridge National Laboratory	http://icon.rice.edu/research.cfm
National Institute for Occupational Safety and Health	Nanoparticle Information Library	The Nanoparticle Information Library (NIL) is intended to help occupational health professionals, industrial users, worker groups, and researchers organize and share information on nanomaterials, including their health and safety-associated properties	http://www2a.cdc.gov/niosh-nil/index.asp
Woodrow Wilson International Center for Scholars and the Pew Charitable Trusts Project on Emerging Nanotechnologies	Inventory of Nanotechnology Health and Environmental Implications	The inventory catalogs global government-funded research into the human health, safety and environmental implications of nanotechnology.	http://www.nanotechproject.org/index.php?id=18

[3.5] Socioeonomic Issues

Despite the challenges and uncertainties of using new technology, many developing countries are pursuing the opportunities nanotechnology has to offer. As described in section 4, South Africa is using nanofiltration membrane technology in small water treatment plants for rural communities. The following sections capture some general lessons from the authors' experience regarding social aspects of successful projects. In addition to the socioeconomic issues described in section 1 and 2, the following sections describe social issues related to the use of technology in projects to provide clean water to communities in developing countries. The comments are based on and informed by the authors' experience with developing and implementing projects to provide water treatment plants incorporating nanomembrane filtration in rural South Africa. They describe the types of issues that need to be considered in order to develop a project that meets community needs and is accepted and embraced by a community.

[3.5.1] Awareness

> ... “people may not be aware of pollutants that cannot be seen, tasted, or smelled.”

Access to water is considered a basic human right in South Africa.[115] The South African government and water-related agencies launched campaigns to provide potable water to rural and peri-urban communities. This was achieved through the establishment of small water treatment plants in an attempt to make water accessible to all.[116] Consumers, particularly in rural areas, may not be aware of efforts to treat community water supplies to ensure good water

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[114] Royal Society and Royal Academy of Engineering, "Nanoscience and nanotechnologies: opportunities and uncertainties," 2003, <http://www.nanotec.org.uk/finalReport.htm>.

[115] The Constitution of the Republic of South Africa, Act 108 of 1996, Cape Town.

[116] B. Netshiswinzhe, "Free Basic Water – Tapping Its Developmental Potential in Rural Areas," 2002, <http://www.mvula.co.za>; and I. W. Bailey, "The Impact of Introducing Treated Water on Aspects of Community in a Rural Community in Kwa-Zulu-Natal," Umgeni Water Report, No. 925/03, 2003; S. J. Modise, and H. M. Krieg, "Evaluation of Nanofiltration for the Treatment of Rural Groundwater for Potable Water Use," WRC Report, No. 1230/1/04, Pretoria, South Africa, 2004; and V.L. Pillay and E. P. Jacobs, "The Development of Small-Scale Ultrafiltration Systems for Potable Water Production," WRC Report, No. 1070/1/04, Pretoria, South Africa, 2004.

quality and quantity. Although water quantity appears to be of more importance than water quality, South African consumers generally do not distinguish between quality and quantity.[117] They define water quality as water that is safe to drink and wholesome.[116] Water quantity is expressed in terms of affordability, accessibility, and availability.[119]

Case studies in South Africa showed that the physical properties of water of smell, taste, and color or appearance are more crucial in assessing water quality than chemical and microbial properties in rural communities.[120] Consumers tended to restrict water quality only to the physical properties of the water. They related good physical water quality to safety, palatability, and effective water treatment. However, it is an established fact that physical properties of water are not always valid water quality indicators. Furthermore, consumers also believed that rainwater is of good quality and therefore safe to drink. This is not necessarily true because rainwater may be polluted with atmospheric pollutant gases. Consumers generally thought that water that was supplied by water service providers is safe to drink or potable.[121]

Consumers in rural communities have their own perceptions of water quality. These perceptions may not necessarily tally with the scientific definition of water quality, and people may not be aware of pollutants that cannot be seen, tasted, or smelled. It is essential to familiarize the community whose water supply is being treated with the scientific concept of water quality and the dangers of pollutants people cannot detect without scientific methods. This would help ensure that the quality of the treated water will be accepted and appreciated.

[3.5.2] Technology Transfer and Capacity Building

The water service providers, government, and the community should be involved from the planning to the implementation stages of a community water treatment project. This would make the community part of the process in the project. The consumers or the community would recognize the fact that they are stakeholders in the water treatment project, and they would understand the objectives of the project and appreciate its benefits.[122] Proper informative procedures are therefore a prerequisite for the acceptance of a water treatment technology by a community and consumers of the service.

> …“the community must be involved at all stages of the water treatment project…”

There are at least two requirements for implementing a new technology for water treatment in a community, particularly in a rural community. First, the community must be exposed to a comprehensive education program that will inform and educate them about the methodology and benefits of the water treatment project. The community should be informed about the quality of the water to be expected after the water treatment. Secondly, the community must be involved at all stages of the water treatment project. For instance, several members of the community should be trained in the operation and maintenance of the new water treatment technology in order to help ensure community ownership of the technology and build local capacity to maintain and operate the equipment.

[3.5.3] Community Ownership and Sustainability

Consumers are stakeholders in utilizing and taking care of the product or service from the water treatment process. The sustainability of the nanofiltration water treatment project can be improved by providing the consumers with the necessary information regarding their basic water services. A sustainable water supply/quantity is only possible if it is affordable, accessible, and available.[123] A rural community will only take ownership of a water treatment project that is reliable and that they can trust. The negative connotations of vandalism and theft are less likely to occur once the community has accepted the nanofiltration water treatment project.[124]

The involvement of the community at all stages of the nanotechnology water treatment project produces transparency that dispels distrust between the parties, the consumers, and water services.[125] This is essential because it empowers and makes the consumer appreciate the procedures involved in the water treatment process and deepens the trust between the parties. Trust is of utmost importance because it minimizes or eliminates misunderstandings and misconceptions about the objectives of the nanotechnology water treatment project. Finally, community ownership and sustainability can be improved through the formation of community structures. These would maintain a communication channel between the consumers and water service providers and would further cement the trust between these parties.

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[117] J. De Fontaine, "Trouble-Shooting Guide for the Domestic Consumer," *WRC Report*, Pretoria, South Africa, 2004.

[118] A. J. Bates, "Water as Consumed and Its Impact on the Consumer – Do We Understand the Variables?" Food and Chemical Toxicology, Vol. 38, No. 1, 2000, pp. 529 – 536.

[119] Modise and Krieg, op. cit.; and De Fontaine, op. cit.

[120] Department of Water Affairs and Forestry, "Quality of Domestic Water Supplies," Assessment Guide, Vol. 1, Department of Water Affairs and Forestry, Department of Health and Water Research Commission, 2003.

[121] Bates, op. cit.; and DWAF, op. cit..

[122] K. Sami and E. C. Murray, "Guidelines of the Evaluation of Water Resources for Rural Development with an Emphasis on Groundwater," *WRC Report*, No. 677/1/98, Pretoria, South Africa, 1998; P. Pybus et al., "The Level of Communication between Communities and Engineers in the Provision of Engineering Service," *WRC Report*, No. TT 133/00, Pretoria, South Africa, 2001; and S. Mathabatha and D. Naidoo, "A Review of Public Participation in the Rural Water and Sanitation Setting," *WRC Report*, No. 1381/1/04, Pretoria, South Africa, 2004.

[123] Modise and Krieg, op. cit.; and De Fontaine, op. cit.

[124] Mathabatha and Naidoo, op. cit.

[125] Mathabatha and Naidoo, op. cit.

[4] case study of a nanofiltration method in South Africa

The following case study describes an existing effort to help a poor community access clean water using nanofiltration membrane technology. It illustrates that developing countries are initiating and implementing projects that utilize nanotechnology. The project describes advantages and disadvantages of the technology used, as well as the social, economic, cultural, and political context in which the project was developed and implemented, including a description of the issues and challenges in developing a project that benefits the community and is sustainable in the long run. This case study provides an opportunity for exploring the potential opportunities and risks of using nanotechnology for improving sanitation and access to clean water in developing countries.

[4.1] Problem Statement

North West Province is situated on a semiarid region of South Africa. There are few surface water sources. The majority of people in the rural areas, making up approximately 80% of the population, depend on groundwater or borehole water for their livelihood. The groundwater is taken directly from the borehole without any prior treatment. Some groundwater sources are contaminated with inorganic nitrogenous pollutants (e.g., ammonium, nitrate, and nitrite ions), chloride, fluoride, calcium, and magnesium ions. These pollutants are a health risk to these rural communities. Nitrate ion is a health risk because it can be reduced to the toxic nitrite ion. Nitrite ions in the stomachs of infants cause methaemoglobinemia. Nitrite ions can also react with amino compounds to form nitrosoamines, which are strongly carcinogenic.[126] Fluoride ions affect dental health, and calcium magnesium ions cause water hardness, which in turn adversely affects body organs such as kidneys, liver, and eyes.

[4.2] Selection of Study Area

Madibogo village is situated in the North West Province of South Africa. It is about 300 kilometers northwest of Sun City, the "Las Vegas" of South Africa. Sun City is 20 kilometers from the platinum mining city of Rustenburg. The village is about 10 kilometers west of Stella, a small farming town, and 20 kilometers south of Delareyville, another small town in the province. It is 100 kilometers northeast of Mafikeng, the capital city of North West Province and location of North West University, Mafikeng campus. It has a population of approximately 40,000 people.

The village was selected in order to highlight the quality of life in a rural area where there is an inadequate basic infrastructure. Some parts of the area have access to roads and electricity. However, as one approaches the most remote areas of the village, these services are no longer accessible to the community. The major challenges facing the Madibogo community are sustainable supply of easily accessible and good-quality water and lack of economic activity. Groundwater is their sole source of water. The water is pumped from four boreholes into a central reservoir and is then reticulated to the village without any pre-treatment whatsoever.

> “The majority of people in the rural areas…depend on groundwater or borehole water for their livelihood. Some groundwater sources are contaminated with inorganic nitrogenous pollutants…”

[4.3] Interventions

Prior to the first democratic elections in 1994, there was no equitable distribution of resources and service delivery. Development was mostly restricted to urban areas and white-owned farms. A strategy was developed 12 years ago to address these imbalances, the Reconstruction and Development Program (RDP).[127] The objectives of the RDP were to improve the quality of life of all citizens, irrespective of race, color, or creed, by introducing infrastructure where there was none and upgrading the existing ones. Providing water that meets the minimum acceptable South African National Standards (SANS) for drinking/potable water, particularly to rural communities, is one of the cornerstones of the RDP. The number of people in rural areas who still do not have access to potable water is currently estimated at 11 million nationwide.

The South African government, nongovernmental organizations (NGOs), parastatal bodies, and the private sector have individually and jointly embarked on projects to supply rural communities with potable water.[128] Water service providers have been contracted to supply potable water to rural communities. These water supply schemes are generally located in the remote rural areas and serve populations of less than 10,000 people. The potable water is typically produced through small water treatment plants (SWTP) whose daily

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[126] M. Hlophe, "Quantitative Determination and Removal of Nitrogenous Pollutants from Natural Waters," Report to the Water Research Commission, Report no.99/1/K5/715, 1999.

[127] C. Chibi and D.A. Vinnicombe, "Promising Approaches in the Removal of Fluoride and Nitrate in Rural Drinking Water Supplies," WRC Workshop, Pretoria, South Africa, 1999.

[128] U. Kolanisi, et al., "A South African study of consumers` perception and household utilization of a rural water service," Master's Thesis, North West University, Potchefstroom, South Africa, 2005.

output is equal to or less than two million liters per day. These SWTP have a simple design to ensure ease of operation and low operating and maintenance costs.

> “North West University (NWU) obtained a research grant…to carry out a research project to test a [nanofiltration] membrane technology…”

The Water Research Commission, WRC,[129] of South Africa is a parastatal body that is responsible for coordinating research in water. The researchers come from tertiary institutions, public and private sectors. The research products are utilized for the development of the community at large. North West University (NWU) obtained a research grant from the WRC to carry out a research project to test a membrane technology unit for the removal of nitrate, chloride, phosphate, and sulphate ions pollutants from groundwater and to monitor rural consumer knowledge of and attitudes toward water purification.

North West University, Mafikeng campus, is carrying out the technological aspect (i.e., the removal of the pollutants), and North West University, Potchefstroom campus, is addressing the consumer aspects of the research project. A pilot membrane treatment plant has been set up at Madibogo village. The pilot treatment plant is located within the premises of Madibogo Batlhaping Primary School. The pilot treatment plant will produce 10,000 liters per day of potable water for 850 pupils and their teachers. The plant will be donated to the community at the completion of the project.

At the onset of the project, researchers of NWU from the Departments of Chemistry and Consumer Sciences held a consultative meeting with the chief of Madibogo village and his councillors before undertaking a groundwater treatment project in his area. The researchers informed the chief and his councillors about the water quality of their area and the need to treat it to remove pollutants. The community has long been aware of the salinity and hardness of their water supply. The researchers were introduced to the chief and his council, and they then outlined all the steps that would be followed in the treatment of the groundwater using nanofiltration technology. The chief subsequently convened a meeting with the community at which he informed them about the quality of the water and how it would be treated.

[4.4] Water Quality

Water quality describes the chemical, physical, and biological characteristics of water, usually in respect to its suitability for an intended purpose. The water quality of Madibogo village is not suitable for drinking because it is polluted with nitrate, chloride, calcium, and magnesium ions. These pollutants have adverse health impacts on consumers. Madibogo groundwater samples were collected in July and October 2005, and analysis results for determinant, result, and the SANS specification are provided in annex 2.

[4.5] Nanofiltration Membrane Technology

Research on membranes in South Africa was begun in 1953 on electrodialysis at the Council for Scientific and Industrial Research (CSIR). The developments in membrane research saw the establishment of initial research on polymer membranes by the Institute of Polymer Studies (IPS) at the University of Stellenbosch in 1973. This research resulted in the establishment of a membrane manufacturing company. Today, membrane research is conducted at several tertiary institutions and private companies.[130] The main thrust of the research is in water treatment as South Africa is a water stressed country. Accordingly, North West University is actively involved in membrane research for water treatment.

[4.5.1] Methodology

Nanofiltration membrane technology
The concentrations of the pollutants (i.e., nitrate, phosphate, sulphate, chloride, calcium, magnesium, and sodium ions) in Madibogo groundwater should be reduced such that the water quality will comply with SANS specifications. Nanofiltration technology was chosen for the treatment of Madibogo groundwater because it is appropriate, affordable, and easy to operate and maintain. Moreover, it is an already established method for water softening and desalination.

Four flat-sheet nanofiltration (NF) membranes and a reverse osmosis (RO) membrane were selected for the water treatment study. The NF membranes were obtained from CHC, a subsidiary of Filmtec. The following filter types were used: NF, NF 90, NF 270, and CTC1. The RO membrane was BW-3040. The membranes had to be characterized to determine the one that would be appropriate for the groundwater treatment. Clean water and retention coefficient studies methods were used for the characterization of the membranes. The study involved two types of experiments: laboratory-scale and on-site.

A dead-end reactor was used for the laboratory-scale experiments. De-ionized (clean) water was used for the characterization of the membranes for the determination of the flux, flow rate, and permeability of each membrane. Approximately a liter of clean water

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[129] “Supporting sustainable development through knowledge creation and dissemination,” Water Research Commission (WRC), Pretoria, South Africa, 2005.
[130] G. Offringa, “Membrane Development in South Africa,” Africa`s First On-Line Magazine, 2002.

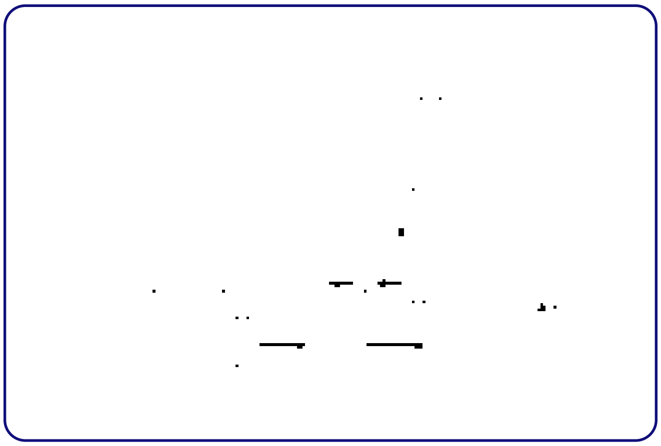
was added into the dead-end reactor, which was fitted with a membrane at one end. The clean water was forced through the membrane at various pressures of nitrogen gas: 5, 10, 15, and 20 bars. A 5.00 cm^3 volume of permeates was collected at each pressure, and the permeation time was recorded. The retention coefficient (R) of the membrane was determined by using single and binary salt solutions. The salts that were used were NaCl, MgCl2, and Na2SO4. The information from these salt solutions studies was also used for the determination of the charge on the membrane. The rejection of the pollutants (i.e., nitrate, phosphate, calcium, magnesium and sodium) was tested for each membrane. The flat-sheet membranes which had good performance were noted.

> "On-site water treatment studies were carried out using a…plant [with a] simple, compact design, which renders the plant readily transportable."

On-site water treatment studies were carried out using a cross-flow reactor (the NF plant). The plant has a simple, compact design, which renders the plant readily transportable. The plant consists of a CIP tank (i.e., a tank that is used for in-situ cleaning of nanomembranes), doping pump, two cartridge filters, high-pressure pump, pressure vessel, and a control box. The plant is approximately 4 meters by 2 meters by 1 meter and is built around a stainless steel frame. The cross-flow reactor was designed and constructed by Malutsa (PTY) Limited, a company based in Cape Town, for NWU, Mafikeng campus, at a cost of ZAR 140,000 (USD 21,423 on May 29, 2006). A spiral wound membrane that is used on the plant's pressure vessel cost ZAR 2,200 (USD 336 on May 29, 2006) and was purchased from CHC, a local company in Cape Town, which is a subsidiary of Filmtec.

The membranes were successively connected to the cross-flow reactor. The experimental setup consisted of a 10,000-liter raw or feed water tank and 10,000-liter product water (permeate) tank. The tanks were connected to the cross-flow reactor. The cross-flow reactor high-pressure pump forces the raw or feed water (Madibogo groundwater) through the membrane, and the permeate is collected in the permeate tank. The plant was designed to produce 10,000 liters of product water per day. A schematic diagram of the experimental set-up is shown in Figure 4.

Figure 4: A Schematic Diagram of the Cross-Flow Reactor Experimental Set-Up



Raw water was permeated through the membrane at four pressures: 16 bar, 18 bar, 20 bar, and 22 bar. The raw water was dosed with an antiscalant. The raw water was pre-treated by passing it through two cartridge filters before reaching the membrane. Two samples, the permeate and brine, were collected after every two hours at each pressure. The samples were collected for eight hours per day for two days in polyethylene 500 cm^3 bottles and were kept in refrigerated cooler bags on-site and transferred to a refrigerator on reaching the laboratory where they were stored at below 40C until analysis. The concentrations of the pollutants (i.e., nitrate, sulphate, chloride, calcium, magnesium, and sodium ions) were determined using a PC spectra.

Operation, Maintenance, and Durability

The plant is very easy to operate and maintain. The plant has built-in safety features; for instance, it simply trips if there is no feed water in the feed tank. The major maintenance is the cleaning of the membranes and replacement of the cartridge filters that are used in pre-treatment. Fouled or clogged membranes are cleaned by a process called chemical in-process cleaning (CIP). The membranes are defouled when they have lost more than 15 – 20% of their normal operating flux. The plant is isolated from the raw water supply and operated in closed circuit using a suitable cleaning solution that is prepared in the CIP tank. The cleaning solution is circulated through the system for a predetermined period. There are three solutions that are widely used for defouling. A 1% sodium hexametaphosphate (SHMP) solution is used to remove biological matter and colloidal foulants. A sodium hydroxide solution (pH 11.5) containing 1% ethylenediaminetetraacetic acid (EDTA), 1% sodium tripolyphosphate (STPP), and 1% trisodium phosphate (TSP) is used for removing silicates, organic, and inorganic solids. A 1% sodium dithionate solution is used to remove metal oxides.[131]

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[131] Malutsa Operating & Maintenance Manual for North West University BWRO Plant, April 2005.

The concentrated raw water from the nanofiltration plant (brine) is collected in a 10,000-liter tank and is used for livestock watering.

Durability of the plant is determined by the NF of RO membrane whose life span ranges from five to six years. There are no special precautions for the disposal of used-up membranes because they essentially consist of ordinary plastic and substrates, for instance, polyester fabric. They are disposed of like any other plastic.

[4.6] Consumer and Socioeconomic Aspects

The consumer aspects of the groundwater treatment project by nanofiltration were undertaken by researchers from the Department of Consumer Sciences, Potchefstroom campus. The objectives of the study were threefold: to determine consumer understanding of the implementation of a water treatment project; to identify aspects that needed to be addressed in an educational program on water treatment; and to develop, implement, and evaluate a water treatment education program.

This study was conducted concurrently with the NF technological aspect, which was being carried out by researchers from the Department of Chemistry, Mafikeng campus, at Madibogo village. It was based on a qualitative strategy through which an exploration was made of the perceptions and utilization of a rural water service by the consumers. A verbal methodology was followed using an evaluation exercise, tape-recorded focus group (i.e., a group in which individuals may air their views freely) discussions, and individual interviews with key community leaders. A random sample of a focus group was obtained by selecting the participants from various community organizations. The researcher used several opportunities to explain the water treatment project to the community. The participants were assured that their participation was voluntary, confidential, and anonymous.

Triangulated instruments, strict sequence with which the focus groups were led, and semistructured interviews were used to ensure accurate and reliable results. Focus groups also afforded the researcher the opportunity to explore unanticipated issues. Semistructured interviews were also used for data collection. Community leaders, for instance, the chief and ward councillor, were interviewed. These interviews consisted of the same questions that were asked in the focus group sessions. Data analysis was conducted by means of content analysis (i.e., a textual investigation of the verbal data through inferences by identifying categories and themes that best represent the data). The tape recordings of the focus groups and semistructured interviews were transcribed and subjected to content analysis.

[4.7] Results

The involvement of the community from the outset resulted in the acceptance of the water treatment project. This suggests that the implementation of proper informative procedures encourages the community to take ownership of the new water treatment project. The study also revealed that rural communities consider water quality in terms of only the physical aspect. The communities were not aware of the microbial and chemical aspects. This suggested that the introduction of a water treatment technology should be accompanied by a well-designed educational program that would inform and educate the users about the advantages and procedures that will be followed in the treatment as well as the quality of water to be expected after treatment. Providing the community with the necessary information regarding basic water services resulted in the community taking ownership of the service.[132] Pupils and teachers at the school have shown a preference for the filtered water.

> “The involvement of the community from the outset resulted in the acceptance of the water treatment project.”

> “All the membranes that were tested have shown selective rejection of the pollutants. Sulphate ions were sufficiently rejected by all the nanomembranes.”

All the membranes that were tested have shown selective rejection of the pollutants. Sulphate ions were sufficiently rejected by all the nanomembranes. Nitrate and chloride ions were all retained by the CTC1 and NF 270 membranes, while the other nanomembranes showed poor rejection in some cases. The CTC1 and NF 270 nanomembranes appear to be appropriate for the treatment of the groundwater at Madibogo village. The plant is still in an experimental stage, and work is in progress to make further improvements.

[4.8] Going Forward

This case study provides an example of a thorough consultative process that included all the stakeholders. Its success can inform

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[132] U. Kolanisi, "A South African study of consumers` perception and household utilization of a rural water service," master's thesis, North West University, Potchefstroom, South Africa, 2005.

other endeavors of this kind. The researchers in this particular case would like to upscale the current NF pilot plant to supply clean water to the whole village of 40,000 people. The project could be replicated in other parts of the developing world that face hard and saline water challenges because of its low-cost design, ease of operation, and low maintenance costs.

The operating costs for a kiloliter of product water from brackish water range from USD 0.16 to USD 0.25 using this nanofiltration technology. The operating costs for reverse osmosis membrane technology are approximately USD 0.36 per kiloliter.[133] These affordable costs make nanofiltration technology accessible to poor communities in rural areas of South Africa. Poor rural communities could source funds from NGOs for the implementation of this technology in cases where funding cannot be obtained from governments.

In addition to the direct humanitarian benefits of improving access to clean water, the technology highlighted in this case study can also promote economic viability in rural communities. For example, a research student who has been working for the pilot project is already planning on acquiring this system to install in her village. With the recent launch of the nanotechnology strategy in South Africa and the need to provide potable water to the majority of the people who have no access to clean water, the authors expect that a wide range of stakeholders will support projects with similar attributes.

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[133] N. Herbert, et al., "Defluoridation, Denitrification and Desalination of Water using Ion-Exchange and Reverse Osmosis Technology," A report to the Water Research Commission, Report no. TT 124/00, 2006.

[5] conclusion

Lack of access to clean water and basic sanitation is affecting millions of people around the world. The well-documented economic, social, and environmental challenges resulting from the lack of access to clean water and basic sanitation have inspired many activities aimed at addressing these problems. Nanotechnology-based water treatment devices are already available and many more are likely to come on the market in the coming years. Due to the pressing human development needs and the availability of promising new technologies, many people have identified nanotechnology for water purification as a high priority area for further action.

The paper demonstrates that nanotechnology research is being conducted in a broad spectrum of areas relevant to water treatment – filters, catalysts, magnetic nanoparticles, and sensors. However, the maturity of research and development efforts is uneven across these areas, with nanofiltration currently appearing as the most mature. Interest in the application of nanotechnology to water treatment devices appears to be driven by several factors including, but not limited to, reduced costs, improved ability to selectively remove contaminants, durability, and size of device. While the current generation of nanofilters may be relatively simple, many researchers believe that future generations of nano-based water treatment devices will capitalize on the new properties of nanoscale materials. Advances through nanotechnology, therefore, may prove to be of significant interest to both developed and developing countries.

As the South African case study illustrates, water treatment devices incorporating nanotechnology may be more mature than many people assume; they are already being used. It also demonstrates that nanotechnology projects are being initiated and implemented by developing countries; the use of these technologies is not limited only to developed countries. Furthermore, while many developing countries are pursuing nanotechnology for economic reasons, the South African case study highlights a project that is being implemented to meet a humanitarian need.

The paper describes the range of issues that should be considered when developing and implementing a water treatment project using nanotechnology. The Bangladesh case study, which features a non-nanotechnology approach for treating water, helps illustrate the range of issues that must be considered by any project developing and implementing a water treatment project. Projects incorporating nanotechnology, however, are likely to raise specific questions about potential environmental and human health risks. The South African case study, for example, touches on these risk issues. The limited review of potential risks may reflect a confidence among project sponsors about the safety of the device used in the case study. It may, however, also indicate a relative lack of information about the risks of nanotechnology, especially information specific to water treatment devices.

This paper is intended as a resource to help people understand the severity of the water and sanitation problem in developing countries, the issues confronting people trying to address this challenge, and the potential opportunities and risks of using nanotechnology to improve sanitation and access to clean water.

It is also intended as a resource for participants in a workshop on nanotechnology, water, and development, which Meridian Institute is convening in 2006. The objective of the workshop will be to develop recommendations that will inform decisions and catalyze actions by stakeholders involved with:

- ☐ Nanotechnology research and development efforts relevant to providing clean water in developing countries.
- ☐ Activities to address potential environmental, health, safety, socio-economic, and other issues related to the use of nanotechnology to provide clean water.

In developing these recommendations, workshop participants will discuss a range of questions including, but not necessarily limited to the following.

- ☐ What are the barriers to improving sanitation and access to clean water in developing countries?
- ☐ How can science, technology, and existing knowledge help address these challenges?
- ☐ What potential does nanotechnology present for addressing these challenges?
- ☐ To the extent that nanotechnology presents opportunities, are there risks and other issues that need to be addressed?
- ☐ What can be done to catalyze or accelerate activities that address these opportunities and risks?

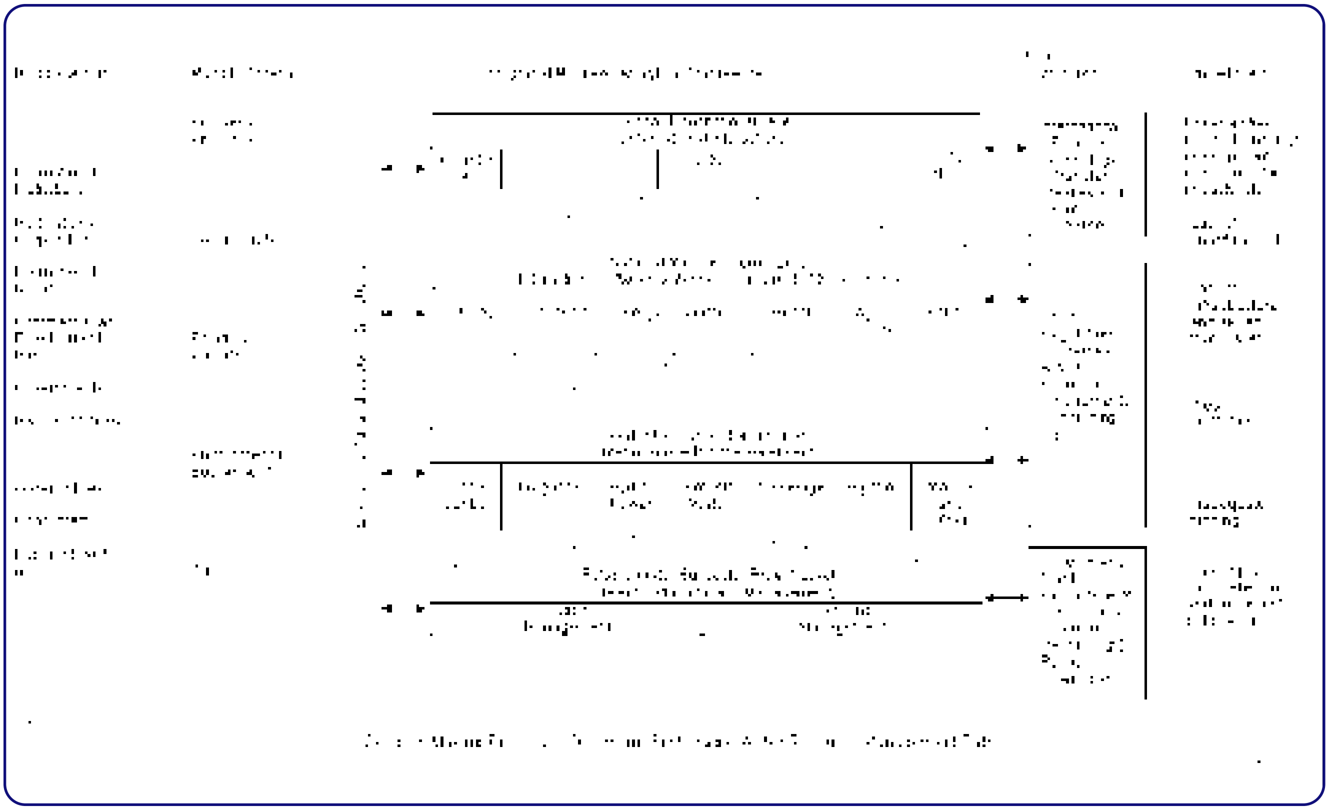
We invite your insights about these questions and feedback about the paper. Please send your comments to Meridian Institute at: nanowater@merid.org.

Annex 1: Sustainable Water Resources Management and Planning

The sustainable water resources management and planning (SWAMP) approach has been proposed to provide an integrated framework for coordination of water resource investment planning and pricing, policy analysis and formulation, as well as policy implementation and management. In many developing countries, spending in the water sector constitutes 10% of all public sector investments, or around 0.5% of total GDP. Thus, even small improvements in the efficiency of water resource development and use would provide major benefits.

SWAMP is a key component of a national sustainable development strategy, and therefore the two should be closely integrated. Effective management of water to achieve desired national sustainable development objectives must be accomplished through an integrated framework because of the many economic and environmental interactions between the water resources sector and other elements of the economy. An integrated approach that includes the three elements of planning, policy analysis, and management will help decisionmakers in formulating policies and providing market signals and information to economic agents that encourage more efficient development and use of water resources. The following figure summarizes the SWAMP concept.

The first two columns of the figure underline the complications facing decisionmakers due to multiple actors and multiple goals. The core of SWAMP is the integrated multilevel analytical framework shown in the middle column, consisting of the following levels: global, national, sector, subsector, and project. It is at the project level that most of the detailed formulation, planning, and implementation of water supply projects and schemes is carried out.



Source: adapted from Munasinghe[134]

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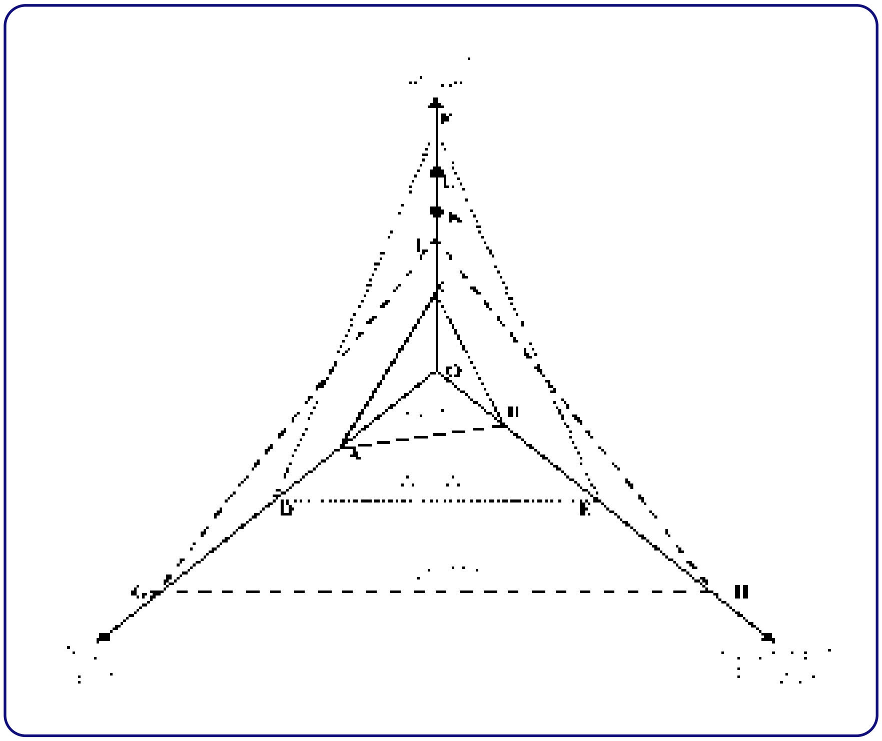
[134] Munasinghe, *Environmental*, op. cit.

SWAMP should result in the development of a flexible sustainable water resource strategy, which may be implemented through water supply and demand policies and programs that make effective use of decentralized market forces and incentives. The figure shows a variety of policy instruments available for implementing SWAMP as well as the most important impediments that limit effective policy formulation and implementation.

Figure 5 shows how a simple sari-based water purification method may be assessed quite simply within the SWAMP framework using MCA. Outward movements along the axes trace improvements in the three sustainable development indicators: economic efficiency (net monetary benefits), social equity (improved benefits for the poor), and environmental protection (reduced water pollution).

Figure 5: Analyzing the Sustainability of Improved Water Quality Using SWAMP and MCA.



Source: adapted from Munasinghe[135]

The policy options may be analyzed as follows. First, triangle ABC describes the existing situation. Waterborne diseases increase both morbidity and mortality rates, thereby causing great economic harm (e.g., loss of earnings, medical expenditures, etc.). Social equity is also low because the poor and disadvantaged are most affected, and overall environmental pollution is bad. Next, triangle DEF indicates a "win-win" future option with the simplified sari filtration technique, in which all three indices improve. Economic losses due to sickness are reduced overall. Social gains accrue to the rural poor, especially women and children. The environmental benefits arise from reduced pollution of water sources.

After realizing such "win-win" gains, the introduction of other options may require trade-offs. Triangle GHI suggests that further environmental and social gains are attainable only at the expense of sharply increasing costs. Thus, more advanced water supply and purification methods (e.g., wells and surface water sources with purification plants and pipe borne supply, or nanotechnology-based techniques) may yield further environmental and social benefits but with increased economic costs. In sharp contrast to the "win-win" move from ABC to DEF, which is unambiguously desirable, a policymaker may not wish to make a further shift from DEF to GHI without knowing the relative weights that society places on the three indices. Such preferences are often difficult to determine explicitly but it is possible to narrow the options. Suppose a small economic cost, FL, yields the full social gain, DG (e.g., by targeting poor households), while a large economic cost, LI, is required to realize the environmental benefit, EH (e.g., widespread water supply and sanitation). Here, the social gain may better justify the economic sacrifice. Further, if purely budgetary constraints limit cost increases to less than FK, then sufficient funds exist only to pay for the social benefits, and the environmental improvements will have to be deferred.

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[135] Munasinghe, *Water*, op. cit.; *and* Munasinghe, *Sustainomics*, op. cit.

Annex 2: Analysis Results for Groundwater Samples

TABLE A: Analysis results for groundwater sample collected in July 2005.

Determinant	Result	SANS specification	
		Recommended maximum limit	Maximum allowable limit
Ph	7.9	6.0 – 9.0	5.5 – 9.5
Nitrate + nitrite as N	13.77 mg/L	6	10
Fluoride as F	0.2 mg/L	<1.0	1.0 – 1.5
Alkalinity as $CaCO_3$	204 mg/L	20 – 300	Not specified – 650
Sodium as Na	81 mg/L	100	400
Magnesium as Mg	69 mg/L	<70	70 – 100
Sulphate as SO_4^{2-}	62 mg/L	200	600
Chloride as Cl-	353 mg/L	<200	200 – 600
Potassium as K	1.5 mg/L	<50	50 – 100
Calcium as Ca	132 mg/L	<150	150 – 300
Electrical conductivity (25°C)	165.0 mS/m	<150	150 – 370
Total dissolved solids	1008 mg/L	<1000	1000 – 2400

TABLE B: Analysis results for groundwater sample collected in October 2005.

Determinant	Result	SANS specification	
		Recommended maximum limit	Maximum allowable limit
Ph	8.2	6.0 – 9.0	5.5 – 9.5
Nitrate + nitrite as N	21.04 mg/L	6	10
Fluoride as F	0.3 mg/L	<1.0	1.0 – 1.5
Alkalinity as $CaCO_3$	328 mg/L	20 – 300	Not specified – 650
Sodium as Na	130 mg/L	100	400
Magnesium as Mg	101 mg/L	<70	70 – 100
Sulphate as SO_4^{2-}	97 mg/L	200	600
Chloride as Cl-	517 mg/L	<200	200 – 600
Potassium as K	2.8 mg/L	<50	50 – 100
Calcium as Ca	183 mg/L	<150	150 – 300
Electrical conductivity (25°C)	241 mS/m	<150	150 – 370
Total dissolved solids	—	<1000	1000 – 2400