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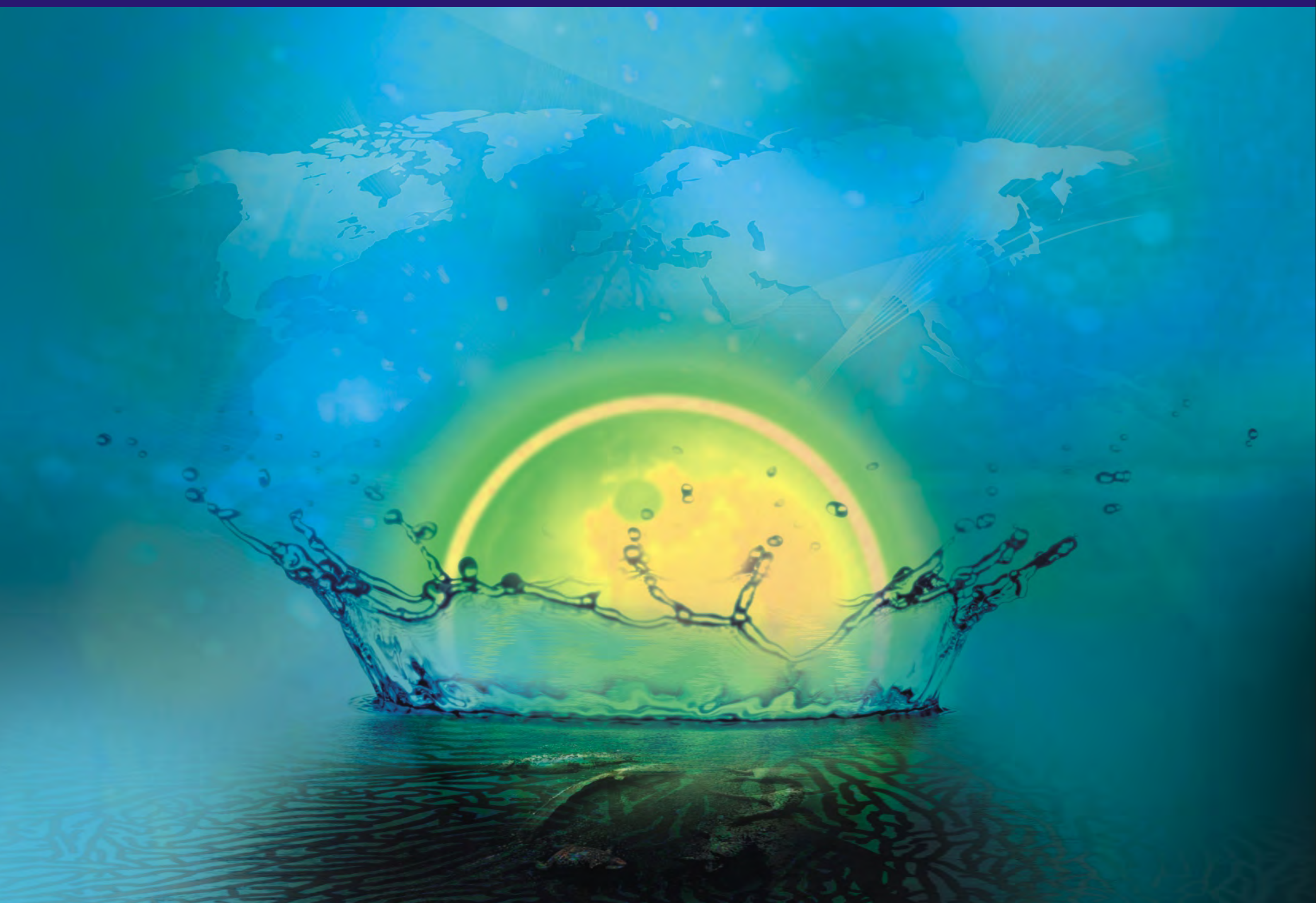

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Borehole Drying: A Review of the Situation in the Voltaian Hydrogeological System in Ghana

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Abstract

Groundwater development for potable water supply for rural people in Africa especially in Ghana has increased significantly over the past decades. The area underlain by the Paleozoic sedimentary formation (Voltaian System) of the country in particular, has experienced this tremendous change. Groundwater in the study area is normally exploited through boreholes fitted mostly with hand pumps. Though the boreholes exhibit variable yields, most of them have yields greater than 13.5 l/min. Research carried out in the area suggests that there is modern and enough recharge, yet borehole drying is a problem especially those with low or marginal yields. A thorough review of the groundwater exploitation in the area, aimed at explaining the circumstances that might lead to these phenomena on the field, has been conducted. The review shows that boreholes with drill yields of usually <20 l/min, especially those drilled in the wet season, constitute the highest percentage of the dried boreholes. Other construction material such as the filter media may also influence the drying process.

Keywords: Borehole Sustainability, Community Water Supply, Ghana, Groundwater Recharge and Depletion, Voltaian System

1. Introduction

The demand for potable water has been increasing since the last three decades due to increasing world population growth. The main sources of water to match these demands include surface waters (from rivers, lakes, streams, ponds) and groundwater. In arid to semi-arid environments, temperatures are usually high and this eventually results in high evaporation rates. Some researchers have reported that surface water bodies that provide water for use especially for irrigation have experienced recent reduction in volume and quality [1,2]. The location and occurrence of surface water make them very susceptible to pollution. Supplying water from these sources especially for domestic purposes require treatment which could be very expensive especially in small settlement communities or towns. In poverty stricken environments, people try to use these waters as they exist, resulting in outbreaks of water borne diseases.

Groundwater which occurs below the surface in the soil pores, fractures, fissures and other weak geological features or zones is relatively protected from bacteriological contamination and evaporation and can be used for domestic and industrial water supply. The ease of tapping the resource at very close point of need gives it an added advantage over surface waters. These merits have caused people to heavily rely on groundwater for domestic, agricultural and industrial purposes.

Groundwater is usually exploited from drilled boreholes, hand-dug wells or spring sources. The latter is usually scarce in many flat or high altitude areas except where the groundwater table rises above the ground surface. Water supply from this type of source is relatively meagre. However, boreholes and hand-dug wells have become the most popular way of supplying groundwater to people in small communities.

It has been reported that about 1.5 billion people worldwide depend on groundwater daily [3]. In Africa, groundwater has proved to be very useful especially for rural water supply for the 47% of the people with access to potable water [4–6]. In this regard, it has been reported that about 250,000 boreholes have been constructed for use in Africa [7]. Though the purpose of these initiatives is to afford sustainable water supply in terms of quality and quantity, there are many reports of abandonment of some of these facilities in many places [6–11]. The reasons assigned to the abandonment include the mechanical breakdown of hand pumps and lack of water in the borehole. It has been reported that hand pumps were observed to be nonfunctional in some communities in Mali where some women preferred to fetch water from shallow hand-dug wells and surface water sources [6]. With availability of modern technology, hand pumps have now been made simple and maintenance could be carried out at the community level where breakdown is no longer a major problem. However, lack of water in the borehole could result from many sources such as lowering of groundwater table and depletion of aquifer storage, improper borehole design and defects from construction, clogging of the filter media and the slots of the screen pipes.

Lowering of groundwater levels and depletion of aquifer storage could arise when there is excessive pumping compared with recharge [12–15]. Excessive pumping could cause intrusion of saline water into fresh aquifers to maintain groundwater levels in coastal areas. On the other hand, if there is improper design or defects in the construction of boreholes the aquifer zones could be sealed. There have been reported cases of situation in some boreholes in Ghana up to 18 m due to broken screen pipes [16]. Consequently, the aquifers are blocked from transmitting water to the boreholes. As reported in literature, water of turbidity greater than 30 NTU causes rapid clogging [17] especially in cases where improper filter media has been used to construct the borehole.

Boreholes fitted with hand pumps are the main sources of potable water supply for rural communities in Ghana. Though the effort for providing potable water is to mitigate high water related diseases in many rural areas especially in the drought prone northern and eastern parts of the country, drying of some boreholes have been reported in some geological formations [18,19]. One of such formations is the Voltaian System which is believed to be late Proterozoic to early Palaeozoic in age [20] and underlain by consolidated sedimentary rocks. Recharge studies conducted using various techniques such as isotopic [19,21] and numerical models have shown that there is fresh and enough recharge to groundwater [22,23]. However, a lot of marginal or low yielding (usually far less than 100 l/min) boreholes dry up especially in the study area after 1- 4 years of usage or less.

In this paper, a review of the borehole drying situation especially in the Voltaian System of Ghana has been carried out to understand the possible causes of it. The review also tends to explain the reasons why redevelopment of some clogged boreholes have not been effective.

2. Study Area

The Voltaian System which cuts across many parts of Ghana, and extends to the Republic of Togo, is the main area where the country depends for its food production. It lies between latitude 11^oN and 6^oN and Longitude 1^oE and 2^oW. The topography of the area is gently undulating in the southern part whereas the northern portion is fairly flat. Close to the geological boundaries, there exist steep hills up to about 450m high in the north and 200-300m high in the south. All the hills trend in the north-east south-west direction. The annual rainfall in the Voltaian Basin ranges from 750 mm in the north to 1600 mm in the south, with evapo-transpiration averaging around 890 mm [24].

Drainage in the study area is enhanced by the Black and White Voltas and the Oti Rivers, and finally flows into the Volta Basin. However, there are smaller rivers which drain into these main rivers. The vegetation in the Voltaian System is wooden savannah in the north and moist deciduous forest in the south. The vegetation in the northern part of the System consists of the savannah plants mainly dense annual and perennial grass, bushes and trees.

The study area is the region with the least percentage of people having access to potable water supply and contributes the highest cases of guinea worm infection and other water borne diseases in Ghana.

3. Geology and Hydrogeology

The Voltaian System occupies about 40% of the entire land area of Ghana (Figure 1) and it is thought to be about 3000 - 4000m thick. It covers most of the northern part of Ghana. In most of these places surface waters flows are ephemeral, occurring only during the wet season. The System consists of inter-bedded rocks including mudstones, sandstones, arkose, conglomerate, shale, and some limestone. The rocks are flat lying or gently dipping except near the eastern margin of the basin adjacent to the contact with the Precambrian rocks where the lower members of the System are gently folded [25]. They are generally consolidated and are not inherently permeable. Possible exceptions, however, do exist in areas where the jointed sandstones, arkoses and quartzite upon weathering have produced permeable surficial materials. Again, the rocks have undergone some degree of

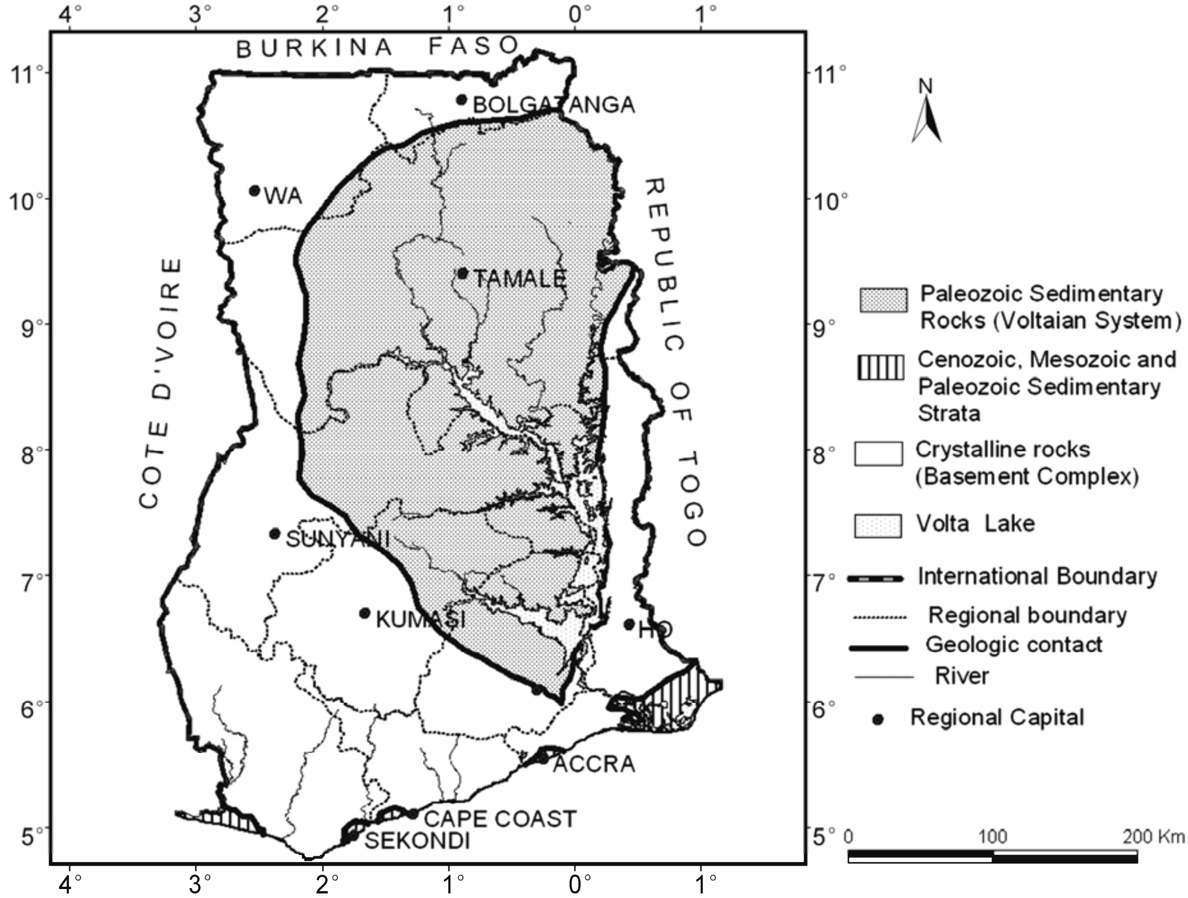


Figure 1. Geological map of the study area (modified after Dapah-Siakwan and Gyau-Boakye, 2000).

tectonic activity and most aquifers are made up of fractures. However, there exist unconsolidated systems dotted in many parts of the basin where good aquifers have been located.

Available records show that for most of the areas maximum borehole depth is about 90m with an average depth of 48.1m [26]. However, there is report of a few boreholes exceeding 100m, even up to about 150 m deep in the far eastern part of the System [19]. Generally, the Voltaian has very poor groundwater potential although some water supplies come from fractures in the argillaceous or loose zones in the arenaceous members [27]. In some portions of the southern part of the Voltaian basin, the weathered or loose zones range from 4 to 20 m thick where many villagers rely on for hand dug borehole development [18,28]. Borehole yields range from 5 to 1200 l/min, static water levels from 1 to 20 m and water table fluctuation averaging about 4m [21,29,30]. The estimated transmissivities range from 0.3 to 270 m^2/day [29]. Most of the aquifers are semi-confined to confined and groundwater quality conforms to the World Health Organization standards. However, there have been few cases of high arsenic and fluoride levels in some drilled boreholes [7,23,31]. Groundwater salinity has also been a major challenge especially in the south-eastern and north-western parts of the basin.

Groundwater recharge varies from location to location, depending on the infiltration capacity of the surface and the permeability of adjacent geologic material shielding the aquifer. Available literature indicates that groundwater recharge in the Voltaian ranges from 3.7-5% of annual rainfall [22,32,33] and groundwater abstraction is estimated to be less than 5% of the annual groundwater recharge [22,23].

4. History of Groundwater Development in the Voltaian

Drilling of boreholes in the Voltaian System began far back in the 1940s [24]. However, the few holes which were drilled did not show good results resulting in the scaling down of groundwater development in the area. In the 1960s, few boreholes were drilled in the south-eastern corner of the System to provide potable water to communities which were displaced as a result of the

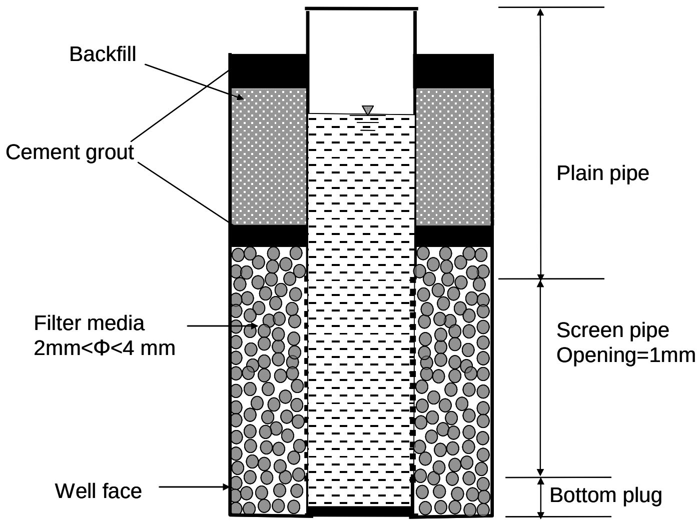


Figure 2(a). Sketch of borehole construction in Ghana.

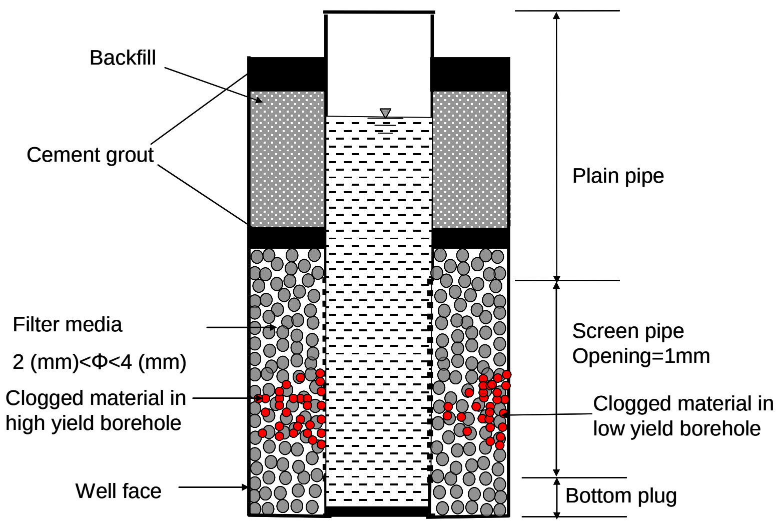


Figure 2(b). Sketch of filter clogging behind the screen.

construction of the Volta Lake [19]. In the mid 1970s, the Canadian International Development Agency (CIDA) entered the north-eastern end of the System to provide boreholes fitted with hand pumps. Based on the experiences gained from those previous drilling, the development of groundwater increased tremendously from the beginning of the 1980s. Within the last two decades many Non Governmental Organizations (NGOs), such as World Vision International, Water Aid, Church of Christ, European Union (EU), United Nations Children's Fund (UNICEF) and CIDA have been carrying out drilling operations in the System. There have been tremendous improvements in the drilling and development technology, and a complete change of siting boreholes using the traditional terrain evaluation to integrated terrain evaluation with geophysical surveys. However, due to the complex nature of the geology, the drilling success rates are still low, estimated to be about 50% with some of the already existing boreholes drying up [7,18,19,29,34].

5. Borehole Construction

Boreholes completed in the Voltaian Systems are lined with PVC pipes of about 140mm diameter. Previously, stainless steel was also used to construct the boreholes but since the inception of Community Water and Sanitation Division (CWSD) in 1994, PVC is the only type of pipes used. In the aquifer zone, a screen is placed to allow inflow of groundwater into the borehole. The annular space (usually~50 mm) between the borehole face and the PVC screen pipe is filled with filter media up to a few meters above the screen height. Figure 2(a) shows a schematic section of a lined borehole. Before a borehole would be considered for construction, it must meet a minimum yield of 13.5 l/min [35]. However, under difficult conditions, yields of at least 5 l/min are considered.

6. Borehole Rehabilitation

Boreholes drilled in the study area are usually community owned, handed over to them after the government or NGO drilling project is completed. It is the usual practice to train local personnel to maintain, repair and manage the boreholes. However, after the boreholes are handed over to beneficiary communities, there is a big issue of monitoring, maintenance and rehabilitation. This might pose a lot of threat to the sustainability of the boreholes as the people living in those communities lack the technology and funds to carry out such technical work [16]. Clogging may then set in with time if the fine particles within the filter material and the slots of the screens are not dislodged regularly.

7. Clogging of Filters

Clogging is a phenomenon that leads to reduction in available pores for fluid flow and resulting in reduction in permeability [36–38]. The cause of clogging could be chemical, biological or physical otherwise known as particle clogging. In the study area, there has neither been any reported case of chemical precipitation leading to chemical nor any case of biological clogging. For the purpose of this paper, the latter is discussed. Generally, particle and water inflows into boreholes are sieved through filters which can accommodate the fines for some time. If the fines are accumulated for a very long time they tend to block the inter-granular pores within the filter media. Although the inflow into the well may not change, the clogged filter media block the groundwater from flowing into the borehole. The end result may be the drying of the borehole. The early days of clogging in boreholes might not be easy to observe especially if the pump installed has a capacity far less than the actual borehole yield. In many cases, borehole cameras are installed to assess clogging. However, this may not show clogging between the filter and the face of the borehole as shown in Figure 2(b). Images from the cameras may only show clogging between the screen holes and the filter media. In this regard, numerical models are required to predict the clogging so that early remediation techniques can be applied.

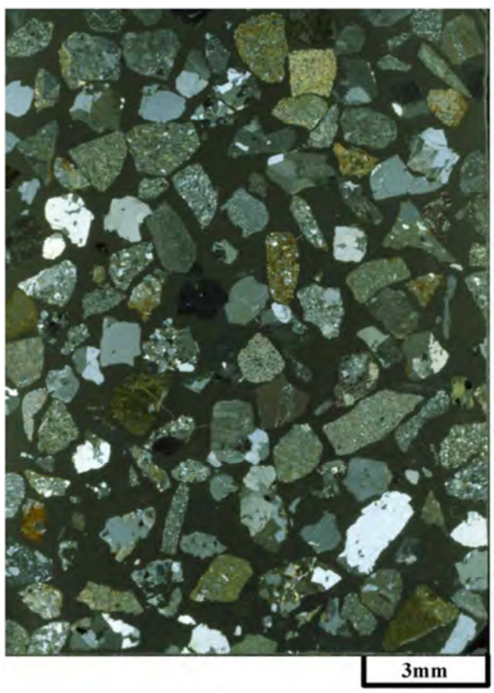
8. Filter Media for Borehole Construction

Field monitoring on some boreholes in the far north-western and north-eastern corners of the Voltaian System was conducted [13]. They monitored the yearly static water levels in 9 boreholes in the north-western and 10 in the north-eastern parts of the study area for 3 years. The authors concluded that the yearly falling water levels in the boreholes were as a result of over-use of groundwater. However, their results, in addition to static water levels from newly drilled boreholes during the monitoring period, suggested that the drying of boreholes may not be due to lowering of groundwater levels or over-use but other uninvestigated factors such as clogging.

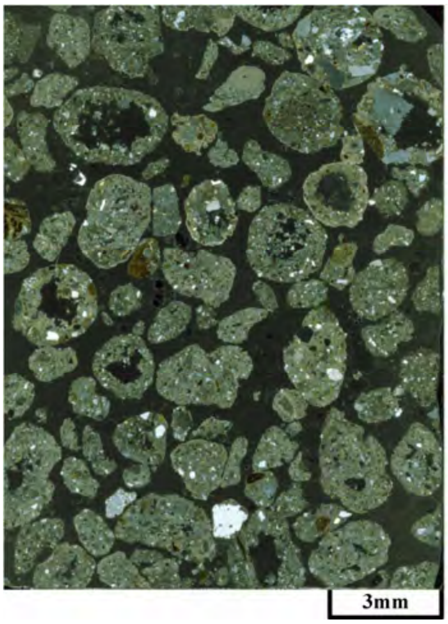
It was observed and reported in literature that irrespective of the geological formation and aquifer material composition, the filter media used for borehole construction were the same in size [16].

As a part of efforts to determine the suitability of filter media used for borehole construction, both mathematical formulations and laboratory observations were made [39,40]. The filter pores were critically examined under the microscope to understand the distribution of the pores within the filter media. The authors compared the pore sizes of filters made from natural river sand and modified soil with cement. The pores were examined by compacting separately (filter media passed through sieves between 2 and 4.7mm sizes) the two types of filters in cylindrical moulds. The samples were impregnated with resin and thin sections taken for microscopic observations (Figures 3(a) and 3(b)).

The results of the microscopic studies are shown in Table 1. The observations showed that the modal pores of the filter media from the river sand were tinny compared with the average pore size. The size of the modal pores of the modified filter was about three times the modal pore size for fluid flow in the natural river sand filter media.



(a) River sand filter



(b) Modified soil filter

Figure 3. Thin section of filter media (2-4.7 mm grain size [40]).

9. Groundwater Coverage and Depletion

Groundwater tapped from aquifers of the Voltaian is the main source of potable water supply for domestic purposes for most communities within the area. It was estimated that about 54.2% of the people depend on groundwater [41]. Tamale municipality and many other communities located close to the Lake Volta, totaling about 45.8% of the population, however, do not depend on groundwater for domestic purposes. Though the area under study covers about 40 % of the land area of Ghana, the population density is very small. Figure 4 shows the estimated number of people living in areas covered by the Voltaian System [41,42]. It is estimated that about 1.83 million people would have been extracting groundwater from the Voltaian as at 2008. On an average, domestic water consumption is about 25 to 50 l/person/day [4,7,22]. The total annual groundwater volume exploited for domestic use could rise to $3.34x10^7$ m^3 in the future. The groundwater recharge from rainfall has been investigated and ranges from 3.7 to 5% of annual rainfall. Rainfall data on the study area for the years 2000 to 2005 varies from 769.5 to 1101.5 mm. Groundwater recharge from rainfall in 2005 would have been 28.5 to 38.5 mm. The total volume of groundwater stored in the System will have been $2.96x10^9$ to $4.00x10^9$ m^3. Despite the fact that groundwater abstraction is less than 1%, the rate of failure of boreholes is high.

Borehole operation survey indicated that out of 492 boreholes, 13% of them had failed within the first 7 years after construction [7]. Though 8.5% of the failure was attributed to pump breakdown, the remaining 4.5% indicated lack of water in the borehole. A relation was reported between borehole drying, yield and the season when it was drilled. Figures 5 and 6 show the relationships between dried boreholes, yield and season of drilling.

Table 1. Summary of results from microscopic study [40].

Filter type (between 2mm and 4.7mm particle size)	River sand	Modified soil
Average microscopic pore size (mm)	0.98	1.02
Numerically determined average pore size (mm)	1.04	1.04
Modal pore size (mm)	0.38	0.96

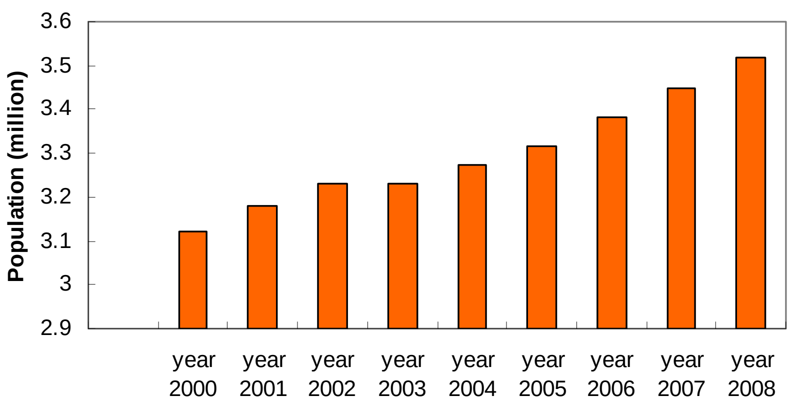


Figure 4. Estimated population living in areas covered by the Voltaian System.

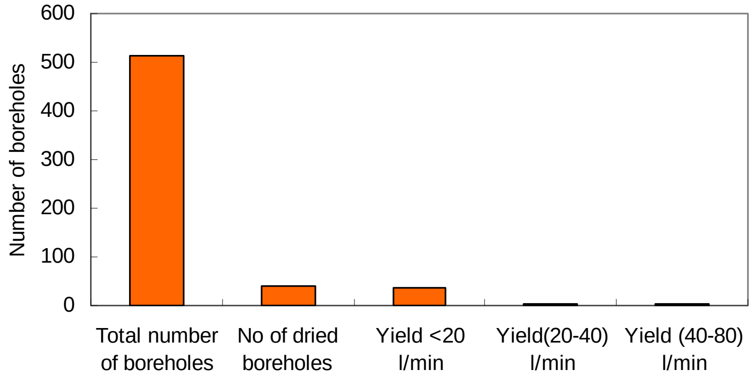


Figure 5. Relation between yield and drying of boreholes.

Figure 6. Relation between borehole drying and drilling season (wet season: July to February, Dry season: March-June).

10. Discussions

Borehole drying is a worldwide issue that needs serious attention. As reported in Mali, lack of confidence on the sustainability of boreholes has made women to prefer surface water [6]. Over 90% of boreholes in Mali were observed to be nonfunctional after one year of completion [8]. Similar reports have been read from South Africa, Uganda, Nigeria and many other African countries [9,16,43]. Borehole drying is a global problem especially in Africa. Regional aquifer heterogeneity might be one of the main causes of the drying. It is reported that over half the annual renewable groundwater supplies in Sub-Saharan Africa are located within only Democratic Republic of Congo, Republic of Congo, Cameroon and Nigeria [44].

In Ghana, the study area has low population density compared with other areas, and depends mainly on groundwater exploited through boreholes. Groundwater is extracted and used mainly for domestic purpose. Field observation in the study area has shown that drying boreholes are generally of low yields at the time of drilling (Figure 5). Boreholes with yields of less than 20 l/min are usually the worst affected. The current research has shown that about 63.4% of the boreholes found to be dried up had drill yields less than 20 l/min.

Drilling programmes are usually time bound, and this influences the rate and season that boreholes are completed. Yields estimated in the wet seasons are normally not reflective of the actual aquifer condition since they might have become saturated. Figure 6 shows that about 78% of the dried boreholes were drilled in the wet season (from July-February). It is generally designed that a borehole should serve about 250 people with daily water need of 25 l/day [4,5]. This implies that a minimum of 8.7 l/min should be required as a standard for a newly drilled borehole to be considered for construction and use. However, to account for water loses and other unforeseen circumstances, a higher minimum yield has been set nationwide to be 13.5 l/min [35].

Quantitative recharge studies conducted in the area showed that total extraction is less than 5% of the estimated recharge [22,23] which also supports the findings from isotopic studies conducted earlier [19,21]. From Figure 4, the highest water demand was estimated to be 3.34×10^7 m^3 in the year 2008. Assuming the recharge from rainfall is 28.5 mm and only 30% of stored water is available for use, about 8.88×10^8 m^3 could be exploited. In this regard, only 3.8% of stored water would have been used, thus confirming the results of previous researches which suggest that there is enough recharge. Interestingly, new boreholes drilled closer to some dried boreholes have always shown static water levels equal to the initial water levels of the dried boreholes, although the existing water levels in the dried boreholes are far below expectation. This further suggests that the drying is not due to depletion of groundwater, as intimated by workers such as [22,23,32,33]. However, availability of enough groundwater reserve does not necessarily mean boreholes cannot dry up. Aquifer heterogeneity can also cause the drying. For hand pump, only 6 hour pumping test is conducted which might not be enough to stretch the aquifer to its limits. Besides this, the pumping tests are carried out on single boreholes which are not usually reliable. The aquifer properties such as storativity and transmissivities might not be accurately estimated especially as most aquifers are located in fractured rock environments.

Borehole construction errors could also be a possible source of the drying issues. When boreholes are constructed, they are normally constructed with plain and screen pipes, and filter media walled around the screen as shown in Figure 2(a). Defective screen and plain pipes could lead to siltation that could block transmission. To ensure good filtering, a filter classification proposed by [45] is suitable for use. The classification requires that $D_{15}/d_{85} < 4$ should be satisfied, where D_{15} means 15% by mass of the filter particles are finer than that size and 85% of the particles are finer than d_{85} particle size of the base material. Although many researchers have opposed the numerical value and particle size pertaining to the filter use [46–48], the ratio serves as a good guide to filter selection. However, it is highly impossible to obtain all the fines during drilling especially in the case of saturated aquifer. Consequently, in borehole construction, a general classification based on certain filter size range is usually prescribed by the local authorities controlling borehole development. For example, filter size ranging from 2-4 mm has been recommended for all boreholes drilled in Ghana by the Community Water and Sanitation Agency (CWSA). The performance of the filter depends on its pore size and the type of fine sediments found in the incoming groundwater at the filter media-borehole interface.

As mentioned earlier, microscopic studies on similar filter material from a natural river source prescribed by CWSA showed that the average pore size was 0.98 mm and the modal pore size available for fluid flow was 0.38 mm [40]. However, results from the modified filter showed that there were nearly equal average and modal pores of 1.02 mm and 0.96 mm, respectively for fluid flow (Table 1). The smaller modal pore sizes can easily get blocked by incoming dirt compared to the larger pore size.

Due to many human activities such as farming and charcoal burning, the land is exposed to erosion and, hence, during recharge especially in the fractured aquifer systems, fines enter the fractures. These sediments may be trapped by the filter media upon entering the borehole face. Although seemly conceptual, as groundwater enters the borehole face the velocity increases, and the change in velocity could cause transportation or deposition of finer material or repositioning of particles of the filter media. Since the filter media is usually of very small radial thickness ranging from about 5 to 10cm or a little more, particles are capable of being pushed through if the force with which they travel is high. In this regard, boreholes with higher yields are capable of providing enough force than low yielding ones. It has been reported that fluid velocity controls particle penetration into porous media and that higher velocities mean farther distance of transportation and deposition [36,38]. In muddy environments, the slurry can be pushed into the borehole or stick around the space between the filter media and the borehole screen. In such situations, it is easy to suck the dirt into the borehole during pumping.

In relatively low yielding boreholes, the entrance force of flowing slurry might not be too high thereby resulting in the deposition of the mud and fines around the point of entrance into the filter media. Continual deposition of the fines leads to clogging and cementation of the filter pores. As the deposition continues, the inflow of groundwater into the borehole is almost blocked. In such case, the water level in the borehole may fall below the general groundwater level as water is drawn from the stored water by the users without replenishment.

Clogging in low yielding boreholes might start from the area between the well face and that of the filter towards the well screen, whereas, those of high yielding may start from between the screen and the filter backwards (Figure 2(b)). In this regard, it is very common to find low yielding boreholes having been redeveloped but no water comes out. The cleaning exercise might not be effective to dislodge the clogged material in the far side of the filter-well surface. On the other hand, because of the proximity of the clogged material to the screen in high yielding boreholes, early cleaning intervention such as rehabilitation may be very effective. This may explain why some low yielding boreholes tend to fail even if attempts are made to clean them.

During pumping, the deposition of fine particles flowing with groundwater into the filter media depends much on the velocity with which they travel and filter pore size. If the weights of the individual fine particles in the flowing water are greater than the forces pushing them in motion, the particles may suddenly come to rest and obstruct the movement of much lighter ones even if their sizes are smaller than the pores in the filter media. If the drag forces are higher and the particles are smaller, then, they may be transported through pores of the filter without deposition. Due to the clayey nature of the rocks in the Voltaian System, the swelling of these particles are possible if the particles are not quickly pushed through the pores of the filter media.

Generally around the borehole face of a low yielding borehole, the velocity of incoming fines cannot be compared with those of high yields. Assuming that all the boreholes of variable yields are located in the same geologic aquifer rich in clay particles, and the same fine particles are found in the inflowing water, then, the low yielding boreholes will quickly get clogged. Filter media clogging could therefore be contributing to the depletion of the water in the boreholes as inflow is adversely affected. Clogging in low or marginal yield boreholes are easy to observe because the yield diminishes abruptly unlike the high yielding ones whose may still match the flow rates of the hand pump for a very long time. Frequent monitoring of the boreholes is therefore very important so that beneficiary communities can be advised.

11. Conclusions and Recommendations

1) Borehole drying is a worldwide issue especially in Sub-Sahara Africa.
2) Drying of marginal or low yielding boreholes in clay rich sediment environments such as the Voltaian System in Ghana affects borehole sustainability and water supply.
3) Borehole drying has a relation with yield and season in which drilling was completed.
4) The review suggests that filter clogging could be a possible cause of the drying of the boreholes. Although many researches have been carried out, not much has been done in relation to clogging especially filter clogging.
5) The type of filter media used in Ghana has smaller modal pore sizes. These sizes can easily be blocked by clay and finer particles.
6) The authors recommend that further work be done to measure the fines transported with groundwater in the area and to select the appropriate size of filter media for the construction of boreholes.
7) Marginal boreholes also need to be rehabilitated regularly to help reduce or dislodge clays and other particles from clogged filter media before cementation.
8) Drilling projects should consider the dry season as most appropriate period for drilling and borehole yield estimation.

12. Acknowledgements

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13. References

[1] J. Kirchner, J. H. Moolman, H. M. du Plessis, and A. G. Reynders, "Causes and management of salinity in the Breede River Valley, South Africa," Hydrogeology J. Vol. 5, No. 1, pp. 98–108, 1997.

[2] L. Changing and Z. Shifeng, "Drying up of the yellow river: its impacts and counter-measures," Mitigation and Adaptation Strategies for Global Chang, Vol. 7, pp. 203–214, 2003.

[3] DFID, "Addressing the water crisis: Healthier and more productive lives for poor people, strategies for achieving the international development targets," Department for International Development, UK, 2001.

[4] A. M. MacDonald, J. Davies, and B. Dochartaigh, "Simple methods for assessing groundwater resources in low permeability areas of Africa," British Geological Society, Nottingham, UK, 2002.

[5] S. B. O. Jallow, 4th World Water Forum, Mexico, 2008. http://www.bvsde.ops-oms.org/bvsacg/e/foro4/19%20marzo/Water/RWSSI.pdf.

[6] B. A. Gleitsmann, M. M. Kroma, and T. Steenhuis, "Analysis of a rural water supply project in three communities in Mali: Participation and sustainability," Natural Res. Forum, Vol. 31, pp. 142–150, 2007.

[7] P. A. Harvey, "Borehole sustainability in rural Africa: An analysis of routine field data," People-Centred Approaches to Water and Environmental Sanitation in 30th WEDC International Conference, Vientiane, Lao PDR, 2004.

[8] World Bank, Performance Audit Report No. 16511, World Bank, Washington DC, 1997.

[9] D. Hazelton, "The development of community water supply systems using deep and shallow well handpumps," Water Research Centre (WRC) Report No. TT132/00, South Africa, 2000.

[10] DWD, "Overview of the water sector, reform, SWAP and financial issues," Directorate of Water Development, Ministry of Water, Lands and Environment, Issue Paper 1, The Republic of Uganda, 2002.

[11] P. A. Harvey and R. A. Reed, "Rural water supply in Africa: Building blocks for handpump sustainability," WEDC, Loughborough University, UK, 2004.

[12] D. E. Kromm and S. E. White, "Groundwater problems," In: D. E. Kromm, White S. E., (Ed.), Groundwater exploitation in the High Plains, University of Kansas Press, Lawrence, Kansas, pp. 44–63, 1992.

[13] J. A. Ayamsegna and P. Amoateng-Mensah, "Well monitoring: World Vision's experience in Ghana," in 28th WEDC Conference on Sustainable Environmental Sanitation and Water Services, Kolkata (Calcutta), India, 2002.

[14] M. R. Llamas and P. Martinez-Santos, "Ethical issues in relation to intensive groundwater use," In M. R. Liamas., E. Custoddio (Ed.), Intensive Use of Groundwater Challenges and Opportunities, Balkema Publishers, The Nertherlands, pp. 3–22, 2005.

[15] J. Samper, "Intensive use of groundwater in the European Union Water Framework Directive," In: A. Sahuquillo, J. Capilla, L. Martinez-Cortina, X. Sanchez-Vila, (Ed.), Groundwater Intensive Use, A. A Balkema Publishers, Leiden, the Nertherlands, pp. 93–101, 2005.

[16] J. A. Akudago, K. Kankam-Yeboah, L. P. Chegbeleh, and M. Nishigaki, "Assessment of well design and sustainability in hard rock systems of northern Ghana," Hydrogeology J., Vol. 15, pp. 789–797, 2007.

[17] Water Treatment, 2008. http://www.who.int/water_sanitation_health/hygiene/om/linkingchap6.pdf.

[18] S. Y. Acheampong, D. Owusu, P. Gyau-Boakye, and N. B. Ayibotele, "Groundwater utilization in the Afram Plains," International Report, Water Resources Research Institute, Council for Scientific and Industrial Research, Accra, 40pp, 2005.

[19] A. J. E. Cobbing and J. Davies, "Understanding problems of low recharge and low yield in boreholes: An example from Ghana," In: D. Stephenson, E.M. Shemang, T. R. Chaoka (Ed.), Water resources of arid areas, A. A Balkema Publishers, London, UK, 2004.

[20] C. Anani, "Sandstone petrology and provenance of the Neoproterozoic Voltaian Group in the southeastern Voltaian Basin, Ghana," Sedimentary Geol., Vol. 128, pp. 83–98, 1999.

[21] S. Y. Acheampong and J. W. Hess, "Origin of the shallow groundwater system in the Southern Voltaian Sedimentary basin of Ghana: An isotopic approach," J. Hydrol., pp. 233, 37–53, 2000.

[22] N. Martin and N. van de Giesen, "Spatial distribution of groundwater production and development potential in the Volta River basin of Ghana and Burkina Faso," Water Int., Vol. 30, No. 2, pp. 239–249, 2005.

[23] A. Lutz, J. M. Thomas, G. Pohll, and W. A. McKay, "Groundwater resource sustainability in the Nabogo Basin of Ghana," J African Earth Sci., Vol. 49, pp. 61–70, 2007.

[24] C. A. Kwei, "Evaluation of groundwater potential in the northern region of Ghana," Canadian International Development Agency (CIDA), Accra, Ghana, 1997.

[25] G. O. Kesse, "The mineral and rock resources of Ghana," A. A Balkema, Rotterdam, 1985.

[26] G. Limited, "Hydrogeological study for borehole siting, training and methodology. 350 Borehole programme in Yendi and East Mamprusi districts," Northern Region Rural Integrated Programme, Ghana, 1991.

[27] L. P. Chegbeleh, J. A. Akudago, M. Nishigaki, and S. N. K. Edusei, "Electromagnetic geophysical survey for groundwater exploration in the Voltaian of northern Ghana", J. Environmental Hydrology, Vol. 17, Paper 9, 2009.

[28] P. S. GMBH, "The 30 well drilling project," Internal Report, Catholic Diocese of Accra, 1984.

[29] P. K. Darko, "Prevailing transmissivity of hard rocks in Ghana," J The Ghana Sci. Assoc., Vol. 2, No. 2, pp. 26–35, 2002.

[30] D. K. Buckley, "Report on advisory visit to water aid projects in Ghana," Unpublished Report, British Geological Survey, Hydrogeology Research Group, Wallingford, 1986.

[31] W. B. Apambire, D. R. Boyle, and F. A. Michel, "Geochemistry, genesis and health implications of fluoriferous groundwaters in the upper regions of Ghana," Environmental Geol., Vol. 33, No. 1, pp. 13–24, 1997.

[32] J. Ricolvi, "Selected case studies: Burkina Faso," In: J. Llyod, (Ed), Water Resources of Hard Rock Aquifers in Arid and Semi-Arid Zones, Paris, United Nations Educational, Scientific, and Cultural Organization, pp. 262–275, 1999.

[33] W. Apambire, "Geochemical modeling and geomedical implications of fluoriferous groundwaters in the upper east region of Ghana," Unpublished Dissertation, University of Nevada, Reno, 2000.

[34] S. Dapaah-Siakwan and P. Gyau-Boakye, "Hydrogeologic framework and borehole yields in Ghana," Hydrogeology J., Vol. 8, pp. 405–416, 2000.

[35] Community Water and Sanitation Division of Ghana Water and Sewerage Corporation, "National community water and sanitation programme, policy, strategy and guide lines," Accra, Ghana, 1996.

[36] S. Veerapaneni and M. R. Wiesner, "Deposit morphology and head loss development in porous media", Environmental Sci. and Tech., Vol. 31, pp. 2738–2744, 1997.

[37] S. Ishida, M. Kotoku, E. Abe, M. A. Fazal, T. Tsuchihara, and M. Imaizumi, "Construction of subsurface dams and its impact on the environment," In: International Conference on Groundwater in Geological Engineering, Bled, Slovennia, September 2003.

[38] D. C. Mays and J. R. Hunt, "Hydrodynamic aspects of particle clogging in porous media," Environmental Sci. and Tech., Vol. 39, pp. 577–584, 2005.

[39] J. A. Akudago, M. Nishigaki, L. P. Chegbeleh, M. A. Alim, M. Komatsu, and K. Kumamaru, "State of the art on filter design and particle clogging; and proposed new numerical approach to redesign," J. Faculty of Environmental Sci. and Tech. Okayama University, Japan, Vol. 13, pp. 63–66, 2008.

[40] J. A. Akudago, M. Nishigaki, L. P. Chegbeleh, M. A. Alim, and M. Komatsu, "Filter choice and its relation to well construction and sustainability in rural water supply," In: Proceedings of the 36th Congress of International Association of Hydrogeolosist, Toyama, Japan, October 26-November 2, 2008.

[41] Ghana Statistical Services, "Summary report of final results, 2000 population and housing census," Ghana Statistical Services, Accra, Ghana, 2002.

[42] CIA World Fact Book, 2008. http://indexmundi.com/g/g.aspx?c =gh&v=2 "Personal communication," Depart-

ment of Geology and Mineral Sciences, University of Ilorin, Nigeria.

[43] S. M. A. Adelana, Personal Communication, Department of Geology and Mineral Sciences, University of Ilorin, Nigeria.

[44] M. Giordano, "Agricultural groundwater use and rural livelihoods in sub-Saharan Africa: A first-cut assessment," Hydrogeology J., Vol. 14, pp. 310–318, 2006.

[45] K. Terzaghi and R. Peck, "Soil mechanics in engineering practice," John Wiley and sons Inco., New York, 1948.

[46] T. Kenney, R. Chachal, E. Chiu, G. Ofoegbu, G. Omange, and C. A. Ume, "Controlling constriction sizes of granular filters," Canadian Geotechnical J., Vol. 22, No. 1, pp. 32–43, 1985.

[47] B. Indraratna and A. K. Raut, "Enhanced criterion for base retention in embankment dam filters," J Geotechical and Geoenvironmental Engg., pp. 1621–1627, ASCE December 2006.

[48] J. L. Sherard, L. P. Dunnigan, and J. R. Talbot, "Basic properties of sand and gravel filters," J. Geotechnical Engg., Vol. 110, No. 6, pp. 684–700, 1984.

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Hydrogeochemical Assessment of Metals Contamination in an Urban Drainage System: A Case Study of Osogbo Township, SW-Nigeria

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Abstract

With increasing urban population, attention had been focused on environmental degradation of urban drainage system with respect to trace/heavy metal contaminations. Such concerns underlie the ever-increasing impacts of urbanization and industrial activities on urban watershed in the developing regions of the world, especially in areas with inadequate land-use plan and poor waste disposal and management practices. Hence, this study highlights the hydrogeochemical assessment of surface water and bottom-sediment samples from an urban drainage system in Osogbo Township, SW-Nigeria with respect to trace metals contaminations.

The results show that the surface water samples have generally low TDS with average value of 362mg/l, while the average dissolved concentrations of the trace metals (Cu, Pb, Zn, Ni, As and Cr) vary from 0.01 to 0.5mg/l. Cu, Cr and As exhibit concentrations similar to the local background concentrations (LBC) in the pristine stream water with low single metal contamination factor (CF $\approx$ 1). Pb, Zn and Ni are 5 folds enriched with contamination factor (CF) of >5 indicating moderate to high contamination. For the sediment phase, the adsorbed concentrations of the trace metals (Cu, Pb, Zn, Ni, As, Cr and Co) vary between 0.1 to 3.1mg/kg. These represent about 1 to 3% of the respective total metal concentrations with average values of 18.2–533.4mg/kg. Also low anthropogenic factor, AF (0.002 to 0.08) and mostly negative values (–5 to –15) of Mueller's geo-accumulation index (I_{geo}) for adsorbed metal contents in the sediments suggest dominant geogenic controls.

However, the total metals concentrations in the sediment phase have high estimated AF of 1.1 to 9.3 and positive values of the estimated I_{geo} (0.9–2.0) and metal contamination index (MCI) of 2.5–8.3. All these suggest a medium to high level enrichment (of 2 to 10 factor) for most of the metals with respect to the local background concentration (LBC) in the basement bedrock units (with the exception of Cr and Ni). This is consistent with the preferential metal enrichment in the sediment phase as indicated by the estimated partitioning/distribution coefficient, K_d of >1 exhibited by the total metal concentrations in the stream sediment. Nonetheless, the correlated high peaks of electrical conductivity of the stream water samples and adsorbed concentrations of some trace metals within the urban stretches are indications of point source inputs of untreated sewage into the drainage system.

Keywords: Urban Drainage System, Heavy Metals Contamination, Bioavailability, Water Quality, Stream Sediments

1. Introduction

Hydrogeochemical surveys of drainage systems have long been employed not only as geochemical exploration tool but to provide information on contaminant metals sources in relation to weathering and erosion transport processes within the catchment area [1–3]. However, a number of studies had shown that trace metals in-puts into the aquatic systems can be through; a) geogenic sources, related to the processes of weathering, erosion and sedimentation of geological units within the catchment area and b) anthropogenic sources, related to human activities that cause enrichment of metals in river waters and bottom sediments [4–8]. In essence, the quality of water in surface drainage system is a function of anthropogenic influences (urbanization, agricultural and industrial activities) as well as natural processes (weathering and catchment erosion) [9].

However, there had been increasing concerns about degradation of urban drainage systems with respect to trace/heavy metal contaminations, in the recent past [5]. This environmental concern is apparently due to the toxicity and perceived persistency of trace metals within the drainage/aquatic systems. Such concerns underlie the ever-increasing impacts of urbanization, agricultural, mining and industrial activities on surface drainage systems. This is more so in the developing regions of the world, especially in areas with inadequate land use plan and lack of proper waste disposal and management practices [10,11].

By and large, there had been a number of global or international efforts such as UNESCO-assisted IGCP 259/360 on standardization of geochemical mapping methodology and Geochemical Reference Network of the IUGS Working Group on Global Geochemical Baseline. These efforts, most of which are in the developed regions of the world, are in parts to address the need for reliable baseline data in respect of trace/heavy metals inputs into the environment. However, there are little and uncoordinated efforts in the developing countries in respect of baseline studies of trace/heavy metals contaminations, even though contamination level may be as high as that of developed/industrialized countries [10,12].

Sediments are said to represent the ultimate sinks for trace/heavy metals in the environment [13–15], because of large specific surfaces for the metal sorption [8]. However, changing environmental conditions may lead to remobilization and release of metal pollutants into the water column and consequently enters into the tropic levels of the food chain within an aquatic/drainage environment. The implication of this is increasing bioavailability and toxicity, which may result to serious health and environmental consequences.

This study presents the contamination assessment of an urbanized drainage catchment in SW-Nigeria, and highlights possible impacts of urbanization and associated anthropogenic activities on the distribution of trace metals in both water and sediment phases of the drainage networks in the study area. In this study we a) describe the distribution of the selected trace metals in both water and sediment phases, b) assess the extent of metal contamination and possible influence/contribution of the underlying bedrock geology and anthropogenic activities within the catchment area and c) provide basis for environmental contamination control/monitoring.

2. Study Area

2.1. Location and Environmental Settings

The Osogbo area where the present study is confined is located within latitude 7°6’N & 7°15’N and longitude 3°17’E & 3°25’E and covers about 268km^2. It is located in SW part of Nigeria (Figure 1). Osogbo-Township is a well-known ancient /cultural urban centers before been named as the capital city of the Osun state in 1991. Subsequently Osogbo township become the focus of both political and socio-economic activities and, therefore, a major recipient of migrants from various parts the state. With a population of about 105,000 in 1991, Osogbo had since witnessed tremendous population growth with an estimated current population of about 220,000 based on the projected 3% annual growth.

Like many emerging cities in developing countries, such rapid urbanization are not usually matched with corresponding adequate urban planning and increase in provision of utility services such as water supply, sewage lines and adequate waste management practices. Therefore, the rapid transformation of Osogbo as ancient/cultural centers into a modern urban enclave had resulted in negative impacts on the quality of the urban drainage system within township area. **Plate 1** and **2** highlight typical environmental scenario where urban drainage systems serve as recipient of household and municipal effluents as well as refuse dumps. Hence, this underpins the need to appraise the quality status and environmental contamination of the urban drainage system in the study area.

2.2. Geological and Climatic Setting

Geologically, the study area lies largely within the Precambrian Basement Complex of Southwestern Nigeria, and belongs to the Pan African mobile belt east of West African Craton. The major rock groups in the study area are migmatite complex (including banded and auguen gneisses as well as pegmatites) and metasediments (consisting of schists quartzites and amphibiolites in places). The dominant basement rocks in Osogbo area (Figure 2) are schist and migmatites, associated with quartzite ridges forming the characteristic undulating terrain. Further details about the geology of the Basement Complex are described elsewhere in past studies [16–18].

Surficial materials are characterized by relatively deeply weathered soil profile or regolith in the low lying areas, due to the relatively humid climatic conditions. Greater proportions of the soils are ferruginous tropical red soils (laterites) associated with Basement Complex terrains. Regionally, soil degradation and soil erosion are generally minimal due to compactness of the surficial material, however, debris wash along the slopes of the hills are common. The area, falls within the lowland tropical rain forest vegetation most of which had since given way to secondary forest and derived savannah. Such secondary vegetations are due to fuel wood production, quarrying and traditional farming practices as well as other developmental projects like road constructions.

The climate is tropical hinterland type with mean annual temperature of about 27°C. Two main climatic seasons are: a dry season which starts from November to early March and a wet season between late March and early November with mean annual rainfall of 1000–1250mm. The drainage pattern is moderately dense and dendritic, dominated by Osun River and its tributaries (Figure 2), which are largely controlled by the structural trends within the Basement Complex terrain.

3. Methodology

3.1. Sampling and Laboratory Analyses

In this study a total number of thirty-eight (38) bottom sediment samples and the corresponding stream water

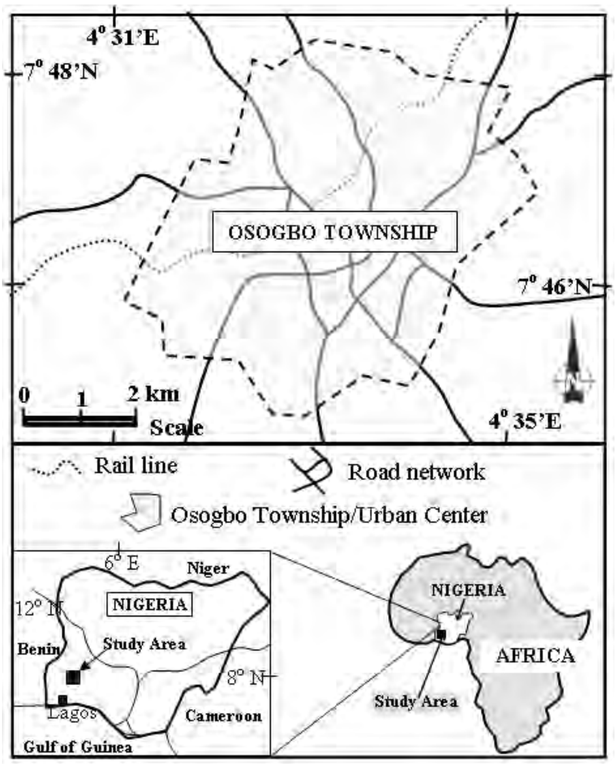

Figure 1. Location Map of the study area with in-set reference map.

Plate 1 and 2. Polluted urban stream channels with sewage water and solid waste dumps.

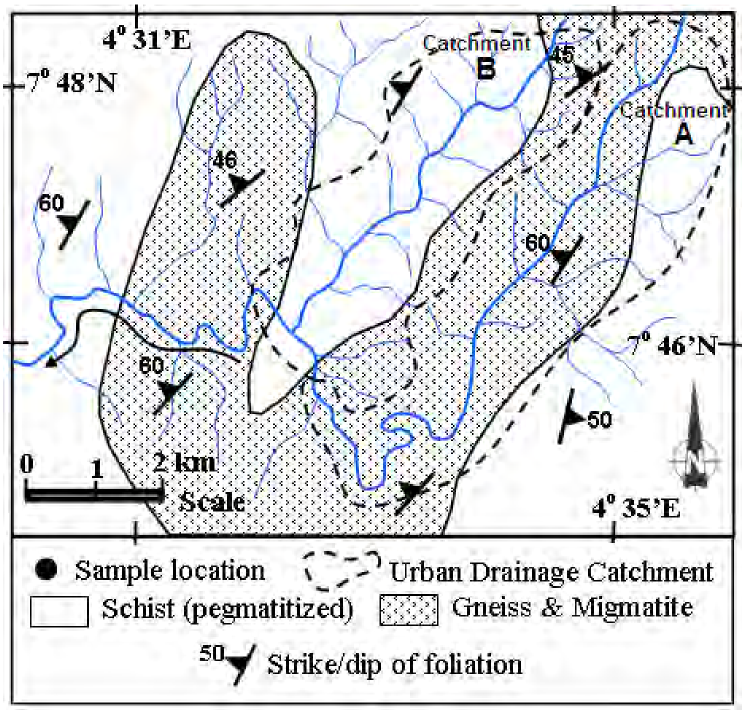

Figure 2. Geological Map of the study area with superimposed drainage system.

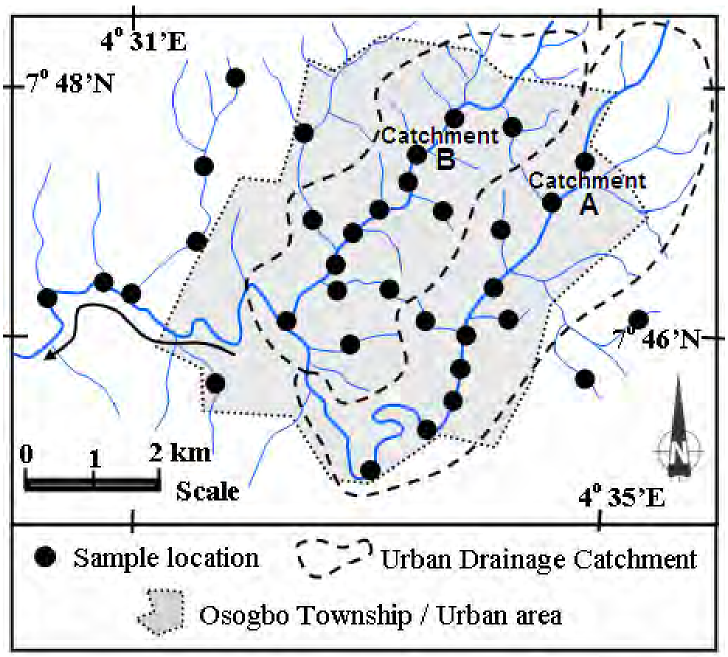

Figure 3. Map of the drainage system of the study area with sample locations.

samples were collected for geochemical analyses. Areal coverage of the sample locations was controlled mostly by accessibility while efforts were made to ensure even distribution within the urban drainage network in the study area (Figure 3). Water samples were collected in plastic bottles following standard sampling procedure [19]. Sensitive physical parameters such as temperature, pH, electrical conductivity (EC) and total dissolved solid (TDS) were determined in-situ using WTW pH/91 pH meter and WTW LF/95 conductivity meter.

Water samples collected were acidified and preserved (refrigerated) prior to analyses of dissolved metal concentrations. Stream sediment samples were collected in clean polythene bags using plastic shovel and sieves to avoid contamination and to drain off the water. The sediment samples were later air-dried in the laboratory, disaggregated and sieved to obtain the clay fractions (<63µm). The use of fine portions (clay fractions) was as a result of their role as metal accumulators, due to their net negative charge and participation in sorption and cation exchange processes. Subsequent to initial sample preparation, the adsorbed content of selected trace/heavy metals (Mn, Cu, Pb, Zn, Ni, As, Cr, Co) in the clay fractions were extracted using 1.0M solution of ammonium acetate. The trace metals concentrations of the extract solutions alongside with the acidified/preserved stream water samples (for all the 38 locations) were then analyzed using ICP-AES method (*Perkin Elmer; model OPTIMA 3000*) at the Biogeochemistry Laboratory, Hiroshima University, Japan. However, about 15 of the stream sediment samples were selected for additional analyses of the total metal concentrations using X-ray florescence (XRF) method (*Rigaku ZSX, Japan)* at the Department of Earth Sciences, Hiroshima University, Japan.

3.2. Data Evaluation

As part of data evaluation, statistical summary and correlation analysis were used to ascertain the interdependence of the parameters. Furthermore, quantification of contamination indices such as anthropogenic factor (AF), enrichment factor (EF), metal contamination Index (MCI) and geo-accumulation index (I_{geo}) for the bottom sediments and contamination factor (CF) for the waters samples were also undertaken. Brief highlights of these indices are presented below, while further details can be found elsewhere in related studies [20–23].

a) Anthropogenic contamination factor (CF) and degree of contamination (C_{deg}): these are quantification of the degree of contamination as single-metal index (CF) and as overall degree of contamination (C_{deg}). The measure is relative to either average crustal composition of the respective metal or to a measured background values from a geologically pristine/ uncontaminated area;

$$CF = C_m/B_m$$

$$C_{deg} = \sum\{C_m/B_m\}_i$$

where i represents the respective metals (i.e. Cu, Pb, Zn, Cd, Fe, Mn); C_m is the measured concentration in sediment or water while B_m is the local background concentration (value) of metal (m) within the pristine area of the catchment. For the C_{deg}, Hakanson recognized four descriptive classes [24], with values of <8 to >32 whereby C_{deg}<8 implies low degree of contamination and C_{deg}>32 implies very high degree of contamination.

b) Elemental contamination index (ECI) and overall metal contamination index (MCI) are expression of single metal contamination within a sample or combined metal contamination for a sample relative to the background values of the respective metal and are expressed as:

$$ECI = (C_m - B_m)/B_m$$

$$MCI = \sum\{(C_m - B_m)/B_m\}_i$$

where, i, C_m, and B_m are as earlier defined above. According to Meybeck *et al.*, [22], MCI was designed to describe general trace elements contamination on a scale from 0 to 100, with MCI of <5 implies very low contamination; 5–10 = low contamination; 10–25 = medium contamination; 25–50 high contamination; 50–100 = very high contamination and >100 implies extremely high contamination.

c) Normalized enrichment factor (n-EF): this was based on the standardization of the analyzed metals against a conservative reference element. Such reference elements (e.g. Sc, Mn, Ti Al and Fe) are usually characterized by low occurrence variability and uniform flux from crustal source-rocks [20,21]. In this study Al was used as a conservative reference metal since it has relatively higher precision of measurement as a major element and also it has been widely used as a normalizing metal in geochemical studies [20,25,26].

$$n\text{-}EF = (C_m/C_{Al}) / (B_m/Al_{-backgrd})$$

where, C_m and B_m are as defined above, while C_{Al} is the measured concentration of Al in sediment or water. $Al_{backgrd}$ is the background concentration of reference element (Al) within the pristine area of the study catchment. Five descriptive categories of enrichment/contamination are defined based on the EF [20] with values of <2 to >40 whereby EF<2 implies deficiency or minimal enrichment and EF>40 implies extremely high enrichment.

d) Index of Geoaccumulation (I_{geo}), as proposed by Mueller, [14] has also been widely used to evaluate the degree of metal contamination in terrestrial, aquatic as well as marine environments [20,27–29]. It is expressed as:

$$I_{geo} = \log_2 [(C_m) / (1.5*B_m)]$$

where C_m and B_m are as defined above, while 1.5 is a factor for possible variation in the background concentration due to lithologic differences. I_{geo} is classified into seven descriptive classes with values of <0 to >5 whereby I_{geo}<0 implies practically no contamination and open-ended I_{geo}>5 implies very high/strong contamination. However, an I_{geo} of 6 is said to be indicative of 100-fold enrichment of a metal with respect to the background value [14].

4. Results and Discussions

The summary of the results of geochemical analyses of the bottom sediment and water samples is presented in Table 1. As presented, the table shows the distribution of average concentrations of the adsorbed, total and dissolved concentrations of selected trace metals in sediment and water phases of the study urban drainage systems.

The average dissolved concentrations of the trace metals (Cu, Pb, Zn, Ni, As, Cr) vary from 0.01 to 0.5mg/l compared to 0.1 to 3.1mg/kg of the adsorbed portions in the sediment phase. However, the dissolved As, Cu and Cr exhibit concentrations similar to the background concentrations in the pristine peri-urban stream waters. Higher concentrations of Pb, Zn, and Ni in the urban stream waters indicate anthropogenic inputs. On the other hand, the adsorbed trace metals in the sediment phase are considerably lower representing about 1 to 3% of the respective total metal concentrations in the sediments with average concentrations of 18.2–533.4mg/kg.

4.1. Assessment of Trace Metal Contamination in the Water Phase

Table 2 presents the summary of dissolved metals concentrations in the water. The average dissolved concentrations of the trace metals (Cu, Pb, Zn, Ni, As, Cr) vary from 0.01 to 0.5mg/l. However, As, Cu and Cr exhibit concentrations similar to the background concentrations in the pristine peri-urban stream waters, compared to relatively higher concentrations of Pb, Zn, and Ni in the analyzed urban stream waters. Furthermore, like other trace metals, Figure 4 highlights the variability of Cu, Pb and Zn in the water column of the urban stream network.

Table 1. Summary of the results of trace metal analyses in water and bottom sediment samples.

Trace Metals	Sediment (mg/kg) N=38 (Adsorbed concentration)			Sediment (mg/kg) N=15 (Total concentration)			Water (mg/l) N=38 (Dissolved conc.)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Mn	1.49	153.2	20.27	775	2248	1204	0.21	12.4	2.08
Cu	0.08	1.60	0.34	38	211	115	0.04	0.09	**0.05**
Pb	0.06	1.50	0.23	50	751	237	0.00	0.14	0.05
Zn	0.58	10.89	3.01	74	964	533	0.08	3.98	0.50
Ni	0.00	0.38	0.03	15	40	30	0.001	0.03	0.01
As	0.07	0.14	0.10	nd	nd	nd	0.07	0.11	**0.08**
Cd	bdl	bdl	bdl	nd	nd	nd	0.001	0.09	0.03
Cr	0.07	0.14	0.09	65	125	87	0.09	0.12	**0.10**
Co	0.12	4.12	0.28	10	37	18	bdl	bdl	bdl
Hg	0.06	0.67	**0.29**	nd	nd	nd	bdl	bdl	bdl

bdl = below detection limit; nd = not determined.

Table 2. Summary of trace metal concentrations in the water phase and metal contamination indices.

Metals	*Dissolved concentration (mg/l) N=32*				CF*	Kd*
	Min	Max	Mean	Control		
Copper (Cu)	*0.04*	*0.09*	*0.05*	*0.04*	*1.4*	6.7
Lead (Pb)	0.00	0.14	0.05	0.003	15.9	16.0
Zinc (Zn)	0.08	3.98	0.50	0.08	5.9	17.0
Nickel (Ni)	0.001	0.03	0.01	0.001	12.2	1.8
Arsenic (As)	*0.07*	*0.11*	*0.08*	*0.07*	*1.1*	1.3
Chromium (Cr)	*0.09*	*0.12*	*0.10*	*0.09*	*1.1*	1.0
Cobalt (Co)	bdl	bdl	bdl	bdl	-	-

*CF = Single metal contamination factor; Kd = Metal partitioning coefficient;
bdl = below detection limit; Control = Conc. of pristine peri-urban stream water sample.

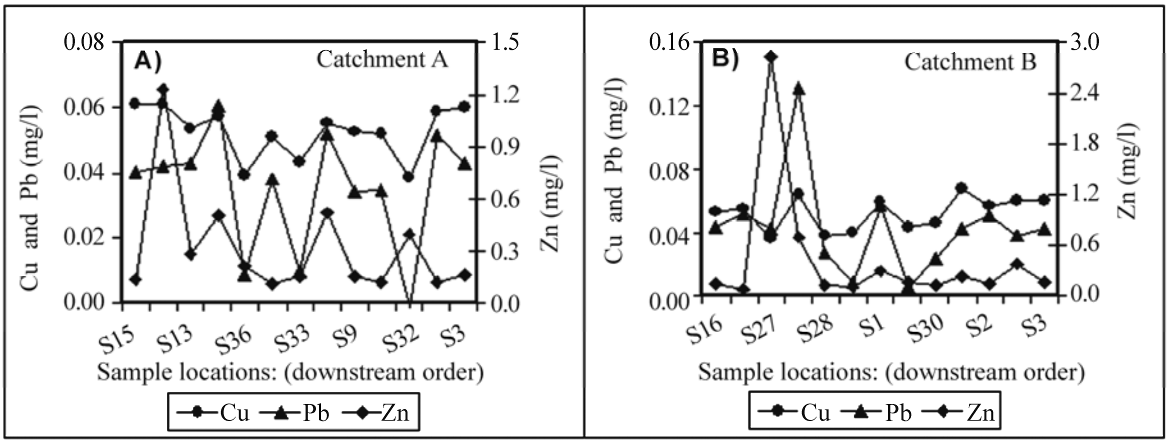

Figure 4. Profiles of trace metal concentrations in stream waters of the drainage catchment A and B.

Table 3. Summary of trace metal concentrations in the sediments and contamination indices.

Metals	**Sediment (mg/kg) N=32 (Adsorbed concentration)**				**Sediment (mg/kg) N=15 (Total concentration)**				**LBC* (mg/kg)**
	Mean	AF	Igeo	MCI	Mean	AF	Igeo	MCI	
Cu	0.34	0.027	-6.3	-0.97	115.2	9.31	2.48	8.31	12.4
Pb	0.23	0.003	-9.2	-1.00	237.2	3.49	0.86	2.49	67.9
Zn	3.01	0.043	-5.7	-0.96	533.4	7.54	2.01	6.54	70.7
Ni	0.03	0.002	9.4	-1.00	30.3	2.65	-9.42	1.65	11.4
As	0.10	0.065	-4.5	-0.93	-	-	-	-	1.5
Cr	0.09	0.001	-10.4	-1.00	86.7	1.04	-0.55	0.04	83.4
Co	0.28	0.066	-5.1	-0.93	18.2	4.42	1.50	3.42	4.1

*Mean = Average metal conc. in mg/kg in sediment; AF = Anthropogenic factor;
MCI = Metal contamination Index; Igeo = Geo-accumulation Index;
LBC = Local background concentration.

Such variability is a clear indication of the fact that the sources of the metal contaminations are related to anthropogenic point-source inputs through discharge of household/municipal wastes within the urban stretches. As a part of further data evaluation, the estimated single metal contamination factors (CF) were studied which indicates that As, Cu and Cr have low degree of contamination in all the analyzed water samples. Other trace metals (Pb, Zn, and Ni) have CF>5 which indicate moderate to very high contamination based on Hakanson classification scheme [24]. This is a consistent with the observed concentrations and hence a further indication of anthropogenic sources of Pb, Zn, and Ni, through wastewater discharge into the stream networks within the urban catchments.

4.2. Assessment of trace metal contamination in the sediment phase

Table 3 presents the average distribution of adsorbed and total concentrations of the analysed trace/heavy metals in the sediment alongside other contamination indices for the study urban stream network. In the analyzed stream sediments, the adsorbed trace metals are considerably lower, with average concentrations of 0.1–3.01mg/kg compared to the respective total metal concentrations of 18.2–533.4mg/kg. Such low proportion of adsorbed total metal concentration is an indication of low bioavailability of adsorbed metal concentrations despite potential geogenic input source.

The variability of the adsorbed Cu, Pb and Zn in the stream sediments along the urban stretches of the stream networks (Figure 5) is a further confirmation of the anthropogenic point source inputs. The estimated AF revealed low enrichment for the adsorbed metals (0.002 to 0.09) within the sediment phase relative to the natural geogenic background concentrations in the underlying bedrocks. This is consistent with the negative values of the estimated I_{geo} (–4.5 to –10.4), which in addition to negative values of MCI (–1.0 to –0.93), clearly suggest dominant local geogenic/pedogenic controls rather than anthropogenic contamination with respect to the adsorbed metal concentrations in the stream sediments.

However, the total metal concentrations in the sediments exhibited high estimated AF of 1.1 to 9.3, positive values of the estimated I_{geo} (0.9–2.0) and metal contamination index (MCI) of 2.5–8.3 (Table 3). These are indications of medium to high level enrichment (of 2 to 10 factor) with respect to the local natural geogenic/pedogenic concentration (LBC) within the catchment area (with the exception of Cr and Ni which exhibit very low enrichment level). Hence it can be concluded that though the adsorbed metal concentrations in the sediment samples suggests little/no contamination, the enrichment revealed by the respective total metal concentrations in the stream sediments is an indication of potential contamination threat due to possible re-mobilization into the water column.

Although the adsorbed metal concentrations in the sediment sample indicate no contamination with respect to the local natural geogenic concentrations in the underlying bedrocks, the estimated K_d values of >1indicate preferential partitioning of most of the metals in the sediment phase (Table 2). This is a further confirmation of potential contamination threat, through possible remobilization into the water phase in response to changes in physico-chemical conditions. In addition, the observed similar peaks/trends of the electrical conductivity (EC) and contamination indices of some trace metals as shown in Figure 6 is also a clear confirmation of anthropogenic point source discharge of waste water within the urban stretches. Similar trend had been reported in urban stream network of Ogunpa River in Ibadan metropolis [23]. Therefore, it can be concluded that despite low adsorbed geogenic metal concentrations in stream sediments, point-source anthropogenic inputs of wastewater into urban stream network can significantly enhance remobilization and bioavailability trace/heavy metals in the drainage environments.

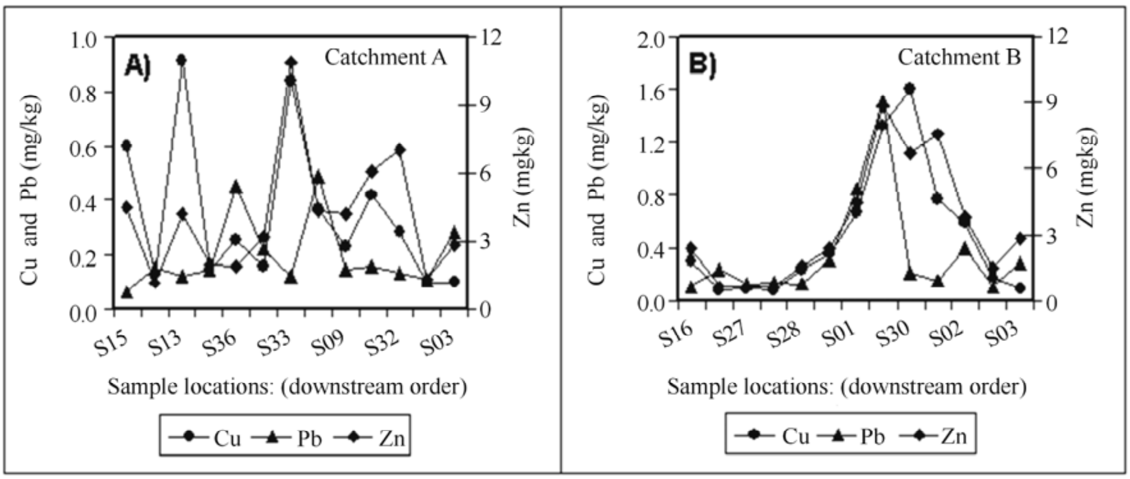

Figure 5. Profiles of trace metal concentrations in bottom sediments of the drainage catchment A and B within Osogbo township.

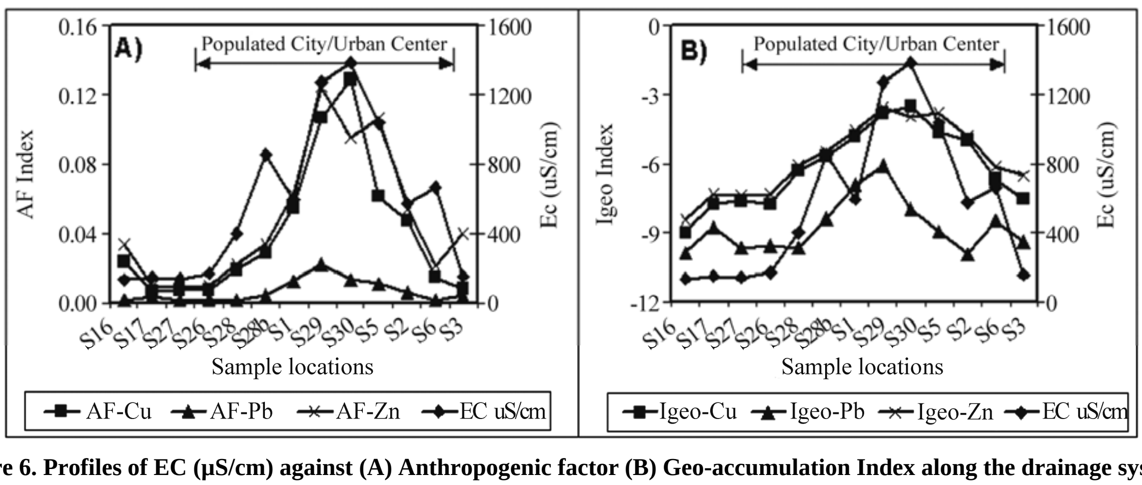

Figure 6. Profiles of EC (μS/cm) against (A) Anthropogenic factor (B) Geo-accumulation Index along the drainage system.

5. Conclusions

This study highlighted the influence of anthropogenic activities in terms of trace metals contamination of urban drainage systems characterized by lack of proper waste disposal/management practices. Assessment of urban drainage system in Osogbo-Township, SW-Nigeria, revealed impacts of untreated wastes discharge on dissolve trace metal concentrations on one hand. On the other hand the study also revealed enrichment of the metals, most especially the total metal concentrations in the stream sediments over the respective baseline concentration. The environmental implication of high enrichment of the trace metals with reference to the baseline (bedrock geology) lies in the potential release and contamination threat through weathering-pedological and erosion-transport processes. This is more so in such humid tropical setting like the present study where apparently high rate of weathering is associated with erosion/run-off of the tropical monsoon rains.

The adsorbed concentrations in the sediment samples indicate no contamination with respect to the background concentration in the underlying bedrocks. However, the dominance of adsorbed concentration of the respective metals over the dissolved contents as indicated by Kd >1 for most of the trace metals is an indication of preferential partitioning in the sediment phase. This is consistent with the enrichment of the total metal concentrations over the baseline concentration, which constitutes potential danger for further contamination due to possible remobilization and re-dissolution into the water phase. Such remobilization could be favored by changes in the physico-chemical milieu (pH, Eh, etc) resulting from the anthropogenic inputs of untreated domestic and municipal effluents from urban catchment.

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7. References

[1] A. G. Darnley, "International geochemical mapping: A new global project," In: A. G. Darnley, A. G. Garrett, (Eds.), International Geochemical Mapping. Jour. Geochem. Explor., Vol. 39, pp. 1–14. 1990.

[2] M. D. Cocker, "Geochemical mapping in Georgia, USA: A tool for environmental studies, geologic mapping and mineral exploration," Jour. Geochem. Explor., Vol. 67, pp. 345–360, 1999.

[3] P. N. Ranasinghe, G. W. A. R. Fernando, C. B. Dissanayake, and M. S. Rupasinghe, "Stream sediment geochemistry of the Upper Mahaweli River Basin of Sri Lanka—Geological and environmental significance," Journal of Geochemical Exploration, Vol. 99, pp. 1–28, 2008.

[4] J. O. Nriagu, "Global inventory of natural and anthropogenic emissions of trace metals to the atmosphere," Nature, Vol. 279, pp. 409–411, 1979.

[5] J. O. Nriagu and J. M. Pacyna, "Quantitative assessment of worldwide contamination of air, water, and soils by trace metals," Nature, Vol. 33, pp. 134–139, 1988.

[6] H. E. Allen, "Standards for metals should not be based on total metal concentrations," SETAC-Europe News, Vol. 8, pp. 7–9, 1997.

[7] M. G. Vijver, J. Spijker, J. P. M. Vink, and L. Posthuma, "Determining metal origins and availability in fluvial deposits by analysis of geochemical baselines and solid-solution partitioning measurements and modeling," Environmental Pollution, Vol. 156, pp. 832–839, 2008.

[8] J. Viersa, B. Dupréa, and J. Gaillardet, "Chemical composition of suspended sediments in World Rivers: New insights from a new database," Science of the Total environment, Vol. 407, pp. 853–868, 2009.

[9] W. Salomon and U. Foerstner, "Metals in the hydrocycle," Springer-Verlag, Berlin Heidelberg, New York. 1984.

[10] M. A. Olade, "Heavy metal pollution and the need for monitoring: Illustrated for developing countries in west Africa," In: Hutchinson T, Meema K, editors. Lead, Mercury, Cadmium and Arsenic in the environment, SCOPE, John Wiley and Sons., pp. 335–341, 1987.

[11] J. L. Mogollon, C. Bifano, and B. E. Davies, "Geochemistry and anthropogenic inputs of metals in a tropical lake in Venezuela," Appl Geochem, Vol. 11, pp. 605–616, 1996.

[12] P. C. Paul and K. C. Pillai, "Trace metals in a tropical river environment-distribution," Water Air Soil Pollute., Vol. 19, pp. 63–73, 1983.

[13] R. J. Gibbs, "Transport phases of transition metals in the Amazon and Yukon Rivers," Geol. Soc. Am. Bull., Vol. 88, pp. 829–843, 1977.

[14] G. Mueller, "Schwermetalle in den Sedimenten des Rheins–Veraenderungen seit 1971," Umschau., Vol. 79, pp. 778–783, 1979.

[15] G. Mueller, "Die Schwermetallbelastung der Sedimenten des neckars und Seiner Nebenfluesse," Chemiker-Zeitung, Vol. 6, pp. 157–164, 1981.

[16] M. A. Rahaman, "Review of the basement geology of southwestern Nigeria," In C. A. Kogbe, (Ed) Geology of Nigeria. Elizabethan Publishers, Lagos, Nigeria. pp. 41–58, 1976.

[17] M. O. Oyawoye, "The basement complex of Nigeria," In: T. F. J. Dessauragie, and Whiteman (Eds), African Geology. Ibadan University Press, Nigeria, pp. 67–78, 1970.

[18] I. B. Odeyemi,.“A review of orogenic events in the Precambrian Basement of Nigeria, West Africa,” Geologische Rundschau, Vol. 70, No. 3, pp. 897–909, 1981.

[19] J. D. Stednick, “Wildland water quality sampling and analysis,” Academic Press Inc., San Deigo, 216p, 1991.

[20] R. A. Sutherland, “Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii,” Environ Geol., Vol. 39, pp. 611–627, 2000..

[21] K. Loska, D. Wiechula, and I. Korus, “Metal contamination of farming soils affected by industry,” Environment International, Vol. 30, pp. 159–165, 2004.

[22] M. Meybeck, A. J. Horowitz, and C. Grosbois, ”The geochemistry of Seine River Basin particulate matter: Distribution of an integrated metal pollution index,” Sci. Tot. Environ., Vol. 328, pp. 219–236, 2004.

[23] M. N. Tijani, K, Jinno, and Y. Hiroshiro, “Environmental ompacts of heavy metal distribution in water and stream sediments of Ogunpa river Ibadan, SW Nigeria,” Jour. Mining and Geol., Vol. 40, No. 1, pp. 73–83, 2004.

[24] L. Hakanson, “An ecological risk index for aquatic pollution control—A sedimentological approach,” Water Res. Vol. 14, pp. 975–1001, 1980.

[25] J. H. Trefry, S. Metz, and R. P. Trocine, “A decline in lead transport by Mississippi River,” Science, Vol. 230, pp. 439–441, 1985.

[26] S. J. Schropp, F. G. Lewis, H. L. Windom, J. D. Ryan, F. D. Calder, and L. C. Burney, “Interpretation of metal concentrations in estuary sediments of Florida using aluminum as a reference element,” Estuaries, Vol. 13, pp. 227–235, 1990.

[27] K. C. Sahu and U. Bhosale, “Heavy metal pollution around the island city of Bombay, India-Part I: Quantification of heavy metal pollution of' aquatic sediments and recognition of environmental discriminants,” Chemistry Geology, Vol. 9l, pp. 263–283, 1991.

[28] M. Singh, A. A. Ansari, G. Mueller, and I. B. Singh, ”Heavy metals in freshly deposited sediments of the Gomati River (a tributary of the Ganga River): Effects of human activities,” Environ Geol., Vol. 29, pp. 247–252, 1997.

[29] B. R. Manjunatha, K. Balakrishna, R. Shankar, and T.R. Mahalingam, “Geochemistry and assessment of metal pollution in soils and river components of a monsoon dominated environment near Karwar, southwest coast of India,” Environ Geol., Vol. 40, pp. 1462–1470, 2001.

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doi:10.4236/jwarp.2009.13022 Published Online September 2009 (http://www.SciRP.org/journal/jwarp/).

Integrated Catchment Value Systems

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Abstract

Historic models of conservation are being superseded by the integration of ecological, economic and social dimensions into a simultaneously sustainable and supportive whole. This transition is evident as South Africa evolves from an apartheid history to novel governance including the equitable, sustainable and efficient use of water within an arid and increasingly climate-challenged landscape.

The concept of 'value chains', established in industrial and government thinking, has been applied to water issues. We explore and extend 'value chain' thinking to cover various important dimensions of water management, taking account of both developed-world assumptions and developing world realities.

This analysis exposes the limitations of linear 'value chains', and the need to join them up into cyclic systems if they are to protect or improve the capacity of water systems to support the sustainable livelihoods and wellbeing of people dependent upon diverse ecosystem services within catchments.

Informed by practical work by the authors in catchments within South Africa, we develop an integrated catchment value system model to support action research dialogues for the delivery of sustainable water services.

Keywords: Catchment, System, Ecosystem Services, Integrated, South Africa

1. Introduction

Recognising that historic approaches to conservation predicated upon excluding people and economic activities from biodiversity or habitat 'reserves' – so-called 'fortress conservation' – had become demonstrably ineffective and unethical, the Ramsar Convention of 1971 [1] ushered in a new era founded upon the 'wise use' of wetland resources through social and economic patterns that do not fundamentally erode the 'natural character' of ecosystems and associated biodiversity. This integration of ecological, economic and social dimensions has since become one of the central tenets of sustainable development. Growing recognition of the interdependence of these three attributes to all habitat types and landscapes was reflected in the 1980 *World Conservation Strategy* [2] and documented as a global consensus in the 1987 UN document *Our Common Future* [3].

The disconnection between social equity and biodiversity considerations is of great significance in South Africa due to its political history. Environmental racism took many extreme forms in apartheid South Africa, a significant element of which was the exclusion of black South Africans from their heritage during the construction of national parks [4]. During the apartheid regime, environmentalism operated effectively as a conservation strategy that neglected social needs [5,6]. Despite the extremely high value of South African national parks for both biodiversity conservation and tourism, they also reflect historic relations of power and privilege which have shaped South African society and which, in turn, confound simple communication of the broader value to society of ecosystems. For this reason, Cock [7] argues that the notion of environmental justice represents an important shift away from the pre-existing traditional authoritarian concept of environmentalism, concerned mainly with the conservation of threatened plants, animals and wilderness areas, broadening it in scope to also include urban, health, labour and development issues. Truly cohesive and sustainable development rests in large measure upon the extent to which all of society identifies with its dependence upon shared supporting ecosystems [8]. Brechin *et al* [9]. argue that, since the protection of nature is today a matter more of politics than ecology, social justice and biological conservation must go hand in hand if they are to flourish in the long term.

The apartheid history of dispossession produced a starkly unequal land ownership pattern and widespread rural poverty, which adds complexity and potential conflict to today's tasks of safeguarding environmental assets as well as undertaking land reform and ensuring access to water and other resources to benefit the historically dispossessed [10]. South Africa is not unique in this regard. Nature conservation and environmental concerns in the USA functioned politically as a coalition of groups with a variety of environmental interests including outdoor recreation, wildlands, open space, public health and pollution, but which largely reflected the tastes of a white political and economic elite [11]. Indeed, the history of clearances and dispossession of 'First Nations' peoples from land to be designated as National Parks in the USA closely mirrors the historic creation of National Parks in South Africa [12].

The concepts of sustainable development and environmental justice are inherently radical and subversive, overturning assumptions and vested interests implicit to prior world views. For example, industrialisation founded on economic and corporate governance models established at the outset of the European Industrial Revolution assumed a limitless pool of natural and human resources available for entraining into the production of financial capital [13]. There is also a history of resistance to allocation of water to 'Instream Flow Requirements', essential to maintain aquatic ecosystems in an intact and functioning state, as it is often seen as taking water away from supporting human needs and economic activities [14].

In the South African context, emerging sustainability and environmental justice principles challenge political assumptions and vested economic interests residual from the nation's history prior to the 1990s. Undertaking a change culture as radical as integration of the three strands of ecology, economy and society is necessarily a protracted process that remains far from complete. Robust scientific concepts are needed to guide this transition, but also a new narrative of the value of protected and restored ecosystems to support the life aspirations of all of the diverse sectors of South African society.

Many assumptions remain to be overcome about the requirements of ecosystems competing with human demands, despite the scientific reality that the many functions performed by aquatic and other ecosystems provide the basic resources and services that support human wellbeing, security and profitability [15,16]. Since the 1990s, there has been growing recognition of the many societal values provided by ecosystems. The numerous 'goods' and 'services' provided to society by the functions within wetland ecosystems were becoming increasingly recognised from the late 1980s [17–19], with societal value provided by forest, oceanic, catchment, rangeland, cropland and many other ecosystem types not long to follow [20–22]. Attempts at monetisation of these many previously unaccounted benefits led to a burgeoning of environmental economic studies, with Costanza *et al*. [15] famously quantifying the cumulative value of global ecosystem services between $US16 and $54 trillion (mean $US33 trillion) per year, largely outside the market and dwarfing the global gross national product of around $US18 trillion. Regardless of uncertainties about both this estimate and its underpinning assumptions, it had become undeniable that the social and economic value of ecosystems was both substantial and substantially overlooked in planning at all scales. Largely externalised from policy and practice, ongoing environmental degradation, not least anthropogenic climate change, threatens to undermine further progress with human development [23]. This trend is also reflected in the ongoing series of *Human Development Reports*, produced annually by the United Nations Development Programme (UNDP) since 1990 (www.hdr.undp.org).

'Ecosystem services', a phrase now subsuming the previous conception of 'goods' and 'services' originating from ecosystem functions, have been advanced by the Millennium Ecosystem Assessment [24] as a strategic mechanism to progressively internalize the interdependence of ecological, social and economic dimensions into sustainable human progress. Interpretation of ecosystem services and discussion of their method of implementation have been approached by various national governments, including in the UK [25,26]. This refocusing on ecosystem services is helpful in that it recognises ecosystems as the source of multiple benefits to society, in polar opposition to the prior conception of 'wildlife conservation' as a constraint on narrowly-framed capitalist social and economic progress. Notwithstanding considerable uncertainty in exactly how ecosystems 'produce' many of these beneficial ecosystem services, there is consensus that biodiversity is needed for ecosystems to function effectively and thus to deliver services [27]. By implication, management of ecosystems to maintain declining or merely a minimum residue of biodiversity is to deny opportunity to current and future generations who equally depend upon these ecosystem services to support their diverse needs. Continued degradation of ecosystems is therefore an infringement of human rights at all scales from the local to the global. Sustainable development is thus as much a moral as a biophysical imperative, dependent upon scientifically-rooted principles to ensure that its implementation is not distorted by vested economic interests [28]. Valuation of natural capital is an essential underpinning of a truly sustainable society and economy [29].

Conservationists across Africa are struggling to find a new model for the protection of species and ecosystems that is politically and economically acceptable to local communities and governments, and which effectively links conservation of biodiversity to social and economic benefits [30]. The interdependency of habitat types within drainage basins provides an integrating framework from which to apply systemic principles to ecosystem management for social and economic wellbeing [31,32].

In this paper, we consider various of the 'value chains' that have been developed in connection with ecosystems, people and economic activities. We then seek to mesh them together into a coherent system that can be used to guide practical dialogue, decision-making and sustainable development. This is undertaken in the context of catchments (drainage basins), acknowledging the limiting role of fresh water and associated services to human development across much of the globe [24,33]. In practical terms, we illustrate our thinking with instances in South Africa, where innovative new water laws [34] and attempts at their implementation create opportunities and case studies relating to novel thinking [35]. In particular, the three driving principles of South Africa's National Water Act 1998 [34] – equity, sustainability and efficiency – provide a sound basis for integrated thinking and implementation of water policies and operational reforms.

2. Value Chains within Catchments

The 'value chain' concept, ascribed to Michael Porter and first introduced in his book *Competitive Advantage: Creating and Sustaining Superior Performance* [36], arose in the field of analysis of industrial and commercial processes. Essentially, it relates to the sequence of activities that a product passes through in a chain of value-adding steps, and is widely used to identify inefficiencies, process enhancements and alternative business models. The concept is, however, of wider value in considering integrated water resource management (IWRM) and other ecosystem-based chains in that it provides a mechanism to link human utility and value (both market and non-market) to the natural processes that create and renew them. It also helps recognise that the means by which nature 'produces' the many ecosystem services from which society benefits is not limitless, and that different uses can have implications for the balance of ecosystem-provided services available to other consumers within catchments.

Given the wide acceptance of the value chain concept for considering cause-and-effect linkages in socio-environmental systems, we set out below five different 'perspectives' on water-related value chains. We then seek ways to integrate these into a coherent systems model for sustainable planning of socio-ecological catchment systems.

2.1. Perspective 1: The Basic Water Value Chain

Recognition of the ecological basis for production of diverse ecosystem services enjoyed by people within catchments is an important primary basis for sustainable and integrated management of water resources [20,24]. In its absence, an 'Industrial Revolution' mindset of water supply and demand might conceptualize the 'value chain' as flowing from rainfall to river to people and to the sea, with any 'unused' water in the river or draining to sea perceived as 'wasted'. This utilitarian model can be seen in those nations enshrining a 'large dam' culture, wherein large-scale engineering is seen as controlling and improving upon nature despite the widespread evidence that it is in reality contributing to declining ecosystems and diminution of services to populations across drainage basins [37,38]. In fact, water is not a static resource, but is in constant circulation in complex cycles at atmospheric, continental, catchment and habitat scales. In essence, it follows cyclic pathways at all these scales, in which living things play a key role. For practical management purposes, the drainage basin, or catchment, represents a pragmatic and finite management unit from which to comprehend and manage water [20,32].

Beneath the catchment landscape scale, at which important physical processes such as orographic effects may contribute to the character and hydrology of catchments, the interaction of water, sediment, solutes and energy with other non-living and living ecosystem components across a range of habitat types occurs through a range of 'ecosystem functions' [16,18]. These functions include water capture, water storage, floodwater detention, physico-chemical purification processes, regeneration of populations of fish, wildfowl, reeds, wetland trees and other vegetation, movement of particulate matter along the river systems ('sediment fluxes'), habitat formation, fluxes of plant nutrients, generation of characteristic ecosystems, and many more besides.

In turn, these functions generate the 'ecosystem services' from which society ultimately derives uses and utility [18,24], and which confer value to humanity in both its market and non-market senses [15,19,39]. The breadth of ecosystem services summarized by the MA is wide, yet itself only partial – covering 'provisioning services' (comprising basic resources such as 'fresh water supply'), 'regulatory services' (including such factors as 'climate regulation'), 'cultural services' (those that enhance human wellbeing i.e. 'aesthetic value') and 'supporting services (underpinning basic life-support processes required to sustain ecosystems such as 'nutrient cycling') – reflecting the dependence of society upon ecological processes for health, wealth creation and quality of life.

The methods by which ecosystems 'produce' their functions are not well understood [27]. However, habitat quality, quantity and location, and the representativeness of that habitat within river systems [40], are known to be important to provide the capacity for these functions as is the role of biodiversity within these habitats [27,41,42].

This basic 'water value chain', incorporating delivery from catchments through functions within habitats and their resultant services, uses and values, is illustrated below in Figure 1.

Of course, ecosystem services can be delivered by highly managed as well as natural ecosystems, although the breadth and balance of services may be altered by modification with consequences for different sectors of society [16,18,43]. In very many cases, industrial exploitation of ecosystems has tended to focus on utilization or management of just one or a few ecosystem services – for examples over-abstraction, damming of natural catchment flows to serve local utility, or waste discharge – and this inevitably comes at a cost to a wide range of other services generally to the detriment of communities sharing catchments [44]. There are, by contrast, positive examples (several reviewed by Everard, 2009) where sensitive management of critical catchment ecosystems and ecosystem functions has delivered a broad range of simultaneous benefits. These include, for example, reliable flows of high quality water, fish recruitment, landscape and tourism protection, and biodiversity gains. Some types of human intervention may therefore be protective or restorative of ecosystems and their supportive capacities. It is then necessary to look at the impacts of different types of human activities upon catchment functioning (*Perspective 2*), the potential for dialogue within society to manage impacts upon and the consequent sharing of ecosystem services (*Perspective 3*), and planned measures to deliver beneficial management consequent from various forms of social contract (*Perspective 4*). Some of these perspectives are encapsulated in some legislation aimed at sustainable catchment management, for example the EU Water Framework Directive.

2.2. Perspective 2: Societal Impacts upon Water Services

Humans are one of the living components of catchment ecosystems, and human pressures often significantly modify catchments at a range of scales varying from broad-scale climatic perturbations and aerial fall-out through to more direct pollution and physical modification of habitat, biodiversity and functioning at scales from the regional to the very local. Some activities alter the functioning of catchments for the express purpose of protecting human development activities (for example flood protection of urban or industrial development in floodplains) or to exploit selected catchment ecosystem services (such as soil fertility exploited by settled agriculture or alternatively dams construction to retain fresh water). One such model of societal impacts upon the 'services' provided by the water environment is contained in the (UK Government) Defra document *An introductory guide to valuing ecosystem services* [25], reproduced in Figure 2.

This 'impact pathway of policy change' model is simplistic; it can not be assumed that changes in policy will result automatically in consistent modification of practice. This is particularly so in the developing world where behavior, particularly amongst people least connected with 'first world' economic activities and their associated benefits, is often far from congruent with national policies. A practical example from South Africa is

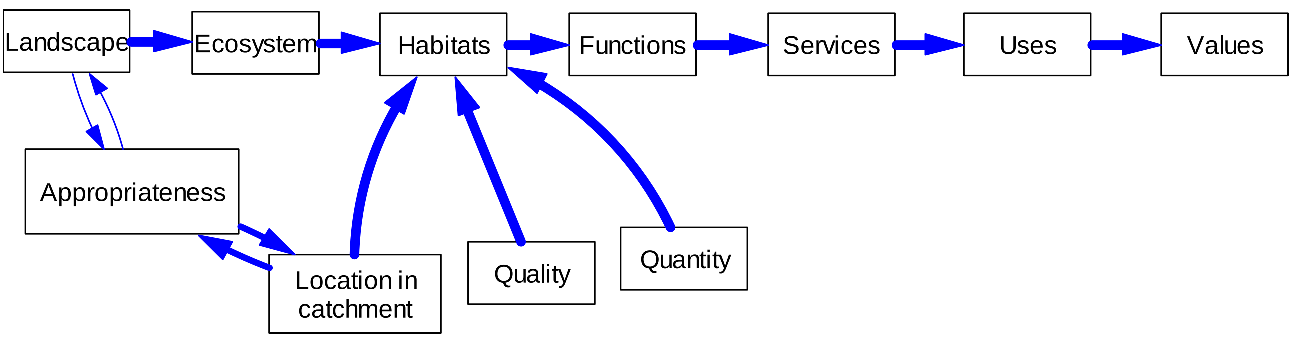

Figure 1. The basic water value chain.

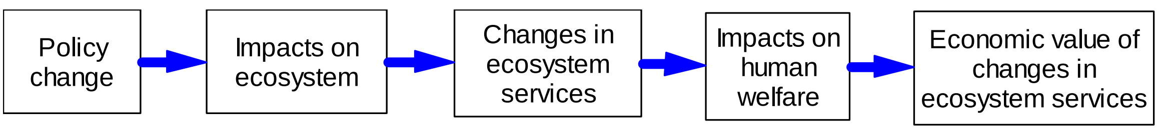

Figure 2. Societal impacts upon water services [25].

collection of fuel wood which, despite the existence of some statutory prohibitions, remains de facto practice amongst rural communities with ramifications for erosion, the hydrology of catchments and biodiversity. Other mechanisms beyond traditional regulation may be more potent in shaping the perceptions of these wider publics, and in modifying human impacts upon ecosystems with consequences for ecosystem services, human welfare and economic value. However, regulation also retains an important role as part of a broader 'package' of instruments that may contribute to modification of social impacts upon water services.

Across the world, various forms of social contract, whether traditional, voluntary or enshrined in formal regulation, have been adopted in recognition of the need to protect the 'carrying capacity' of catchment ecosystems supporting the diverse needs of catchment communities. Regulation of effluent released into catchments is now commonplace in the developed world, implemented to protect the various uses to which river reaches are put based generally upon sets of 'use-related' water quality standards [45]. Controls on catches from fisheries, harvesting of reeds, timber, birds and other catchment products, and a range of other agreements to limit impacts upon ecological integrity are commonly encountered as an expression of public agreement to protect the integrity of aspects of ecosystems of significant economic and/or cultural value. Many nations have codes of good agricultural practice as a basis for limiting the negative environmental impacts of agriculture and other forms of land use [46], intended to protect the functioning of catchments from overuse or misuse by a minority. Of course, the practical observance and enforcement of such policy measures is often at considerable variance with intentions, particularly in developing regions of the world.

Market incentives play an influential role in stimulating behaviour change. When markets ignore ecological 'carrying capacity' and the rights of downstream communities, they can accelerate erosion of essential ecosystem services. However, their potency in changing behaviour can also render them beneficial and particularly in regions where traditional regulation is less effective or largely ignored. For example, informal sectors, particularly those closest to a subsistence level and in rural communities, do not generally respond to laws, which are also often poorly enforced, but they will respond to markets. This is particularly the case where land ownership issues, historic water rights and other vested interests can confound optimal sharing of ecosystem benefits across catchments. Subsistence farmers, and other such constituencies of the 'informal economy' of catchment populations in developing countries, can represent a substantial element of catchment communities; their behaviour can have a major cumulative impact on rural catchments. Where positive incentives for behaviour change feed back to improved value and 'quality of life', markets may be a key instrument leading to either more or less sustainable behaviours. This then highlights the need to create appropriate markets to maximise the benefits of all within catchments. This principle may also apply in developed countries, with markets for ecosystem services playing a key to role in upland catchment management to secure the water supply of New York City and in the SCaMP scheme in north west England (both reviewed in this context by Everard [47]).

In a free market economy, wherein no such market is created for trading in 'ecosystem services', people developing 'upstream' areas of river catchments are able to benefit from the use or conversion of sensitive habitat whilst not bearing the costs of loss or alteration to functioning elsewhere within the catchment system. Correspondingly, those downstream may be unaware of the management conditions upstream that perpetuate the ecosystem services upon which their land and water uses depend [31,32,48]. However, opportunities exist within development planning and water licensing systems to require mitigation measures to address significant impacts upon ecosystem services. For example, consent for a 'water hungry' development, such as a major new factory or renewal of a water abstraction license for commercial forestry, could be granted on condition that investment was made available for upstream habitat improvement to increase the yield of water from the catchment. Even though the quantitative science is currently uncertain, we already understand the principles adequately to be confident that such a mitigation measure would also help deliver wider benefits to others within the catchment as well as being beneficial to wildlife.

This mix of formal, market and informal drivers of behaviour change with respect to the desire for more sustainable societal impacts upon water services are illustrated in Figure 3.

All of these measures – policy and perception including market signals and cultural values – have strengths and weaknesses in the effective engagement of all catchment stakeholders around a commonly-understood narra-

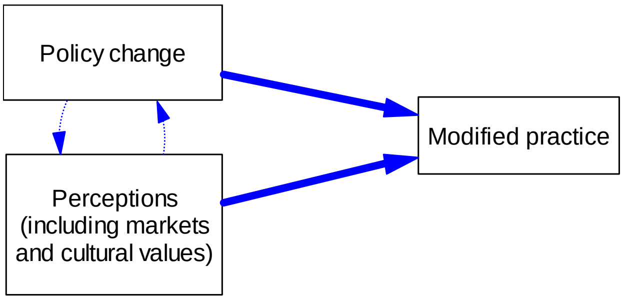

Figure 3. Societal impacts upon water services.

tive relating to water and equitable sharing of its many ecosystem services.

2.3. Perspective 3: Social Dialogue about Water

Social dialogue within catchments concerning the value of ecosystems in supporting societal wellbeing and potential is generally not expressed in technical terms such as those discussed above. Instead, social discourse generally revolves around enjoyment of the benefits of ecosystem services, or suffering from their limitation. These include, for example, services such as fresh water for domestic, agricultural or industrial uses, the vitality of fisheries, fertilisation of floodplains, flooding of developed land, the sense of place within a landscape enjoyed by a community, or the contribution of a changing river reach or forest to cultural character. Most of societal (including industrial and agri-business) identification with catchments occurs at the level of 'uses' and their resultant 'values' flowing as benefits from catchments (as already elaborated in Figure 1). These include, for example, supply of water, dilution of liquid wastes, navigation, viable fisheries (commercial or recreational), hydroelectric generation, fertilisation of floodplains, irrigation of crops, and so forth. Given the significant influence of society upon catchments, and the reciprocal shaping of social and economic patterns by catchment processes, it is legitimate to consider catchments as much social constructions as ecological ones [49]. This is manifestly the case where, for example, inter-catchment transfers and wastewater works generate new and bigger flows, or where large-scale dams alter catchment hydrology.

Identification of the catchment as a finite source of the resources that can potentially meet the competing needs and requirements of different sectors of society within catchments ('catchment communities') provides a basis for dialogue about the interdependence of different catchment uses. It also offers a platform for dialogue about options for catchment development, as all changes to the management of ecosystems and 'harvesting' of ecosystem services, both deliberate and unintended, will inevitably result in different 'winners and losers' through its influence on the suite of ecosystem services delivered throughout the catchment. Social dialogue about catchment use has to take account of the 'package' of interdependent ecosystem services occurring within a catchment, and the sharing of these services amongst the catchment community without one sector creating widespread disadvantage or long-term insecurity for others.

A simple example of this is how an off-channel fish farm may benefit a few people locally but may be detrimental to the self-sustaining river fisheries that support the needs of many other people within the catchment. A more complex example is that of a major dam designed to maximise the local provision of selected ecosystem services (primarily water supply, power generation and potentially some flood protection and/or lake fishery benefits) for clearly-articulated benefit of a chosen few people (who may be local or distantly connected by piped infrastructure). However, dam construction and operation generally tends to compromise the broader suite of other ecosystem services delivered across the whole drainage basin to the detriment of many more people dependent upon the wellbeing of fish and other wildlife stocks, fluxes of silt and nutrients along river corridors, water flows adequate to eliminate waterborne disease vectors, the natural fertilisation of floodplains for seasonal cultivation and grazing, etc. [50]. Inclusion of all constituencies within catchment communities is central to equitable social negotiation and outcomes, ensuring that those traditionally marginalised or excluded from governance decisions and shares of catchment services are given a voice. It is sometimes argued that indigenous peoples are 'closer to nature' and therefore more likely to think systemically [51]. It is generally true that traditional lifestyles are most directly dependent upon ecosystem services such as water collection from streams, fertilisation of riparian grazing, informal fisheries and so on, and that these people are therefore often the most vulnerable to the water use practices by others that erode the general 'carrying capacity' of the catchment. However, it is also true that all people dependent upon ecosystem services, including industries and municipalities remote from habitats critical to the supply of those services (such as water abstracted for mass supply from lowland rivers or dams which is dependent upon the water capture, storage and purification functions of wetland and upland areas of catchments) will be affected by degraded ecosystems.

The potentially deleterious interaction of social activities within catchment ecosystems has given rise to a great deal of historic water-related legislation in the developed world. This may particularly reflect the implications of unsympathetic uses (i.e. waste disposal, over-abstraction, over-harvesting of fish, wildfowl or other resources, etc.) for public health and other uses of river systems to which catchment communities aspire [45].

Understanding of the wide suite of uses and values stemming from ecosystem services, upon which different social and geographical sectors within catchment communities depend and which communities to a greater or lesser degree generate (via their use or abuse of the system), provides a basis for dialogue within catchments upon the relative apportionment of benefits to different sectors of society. This 'social negotiation' value chain is illustrated in Figure 4.

In recent years, there has been a substantial development in techniques for managing this type of social negotiation. Essentially, this requires a social space to be created and held, in which different interest groups can

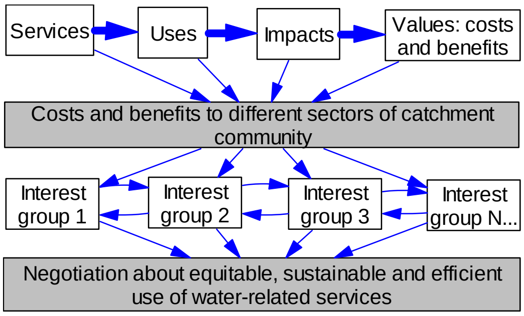

Figure 4. 'Social negotiation' value chain.

express their perspectives on the services, uses, costs and benefits that they see as flowing from (in this case) catchment ecosystems [35,49]. Within this dialogic space, interest groups are required to hear each other's perspectives and then, from a position of enhanced understanding, negotiate agreement on how these services, uses, costs and benefits are to be shared. This decision then helps determine necessary management priorities to deliver commonly-held goals.

Under traditional cost–benefit analysis, these different values and perspectives tend to be collapsed at the outset into the value set of those facilitating the dialogue and/or of more powerful interest groups [50]. By contrast, more recent forms of social appraisal have developed which employ a wide range of approaches and techniques to enable a more open or deliberative process of learning and negotiation between different stakeholders [52–55]. Some of these methods are shown in Figure 5.

2.4. Perspective 4: Protection or Enhancement of Catchment Capacity

Historic patterns of development have degraded the quality and extent of habitat types throughout the world [24], with wetlands a particularly vulnerable set of habitats readily degraded to the detriment of many who depend upon their ecosystem services [18,33]. Whilst the methods by which the functions of catchments 'produce' the diverse services of human benefit are still relatively poorly understood [27], we can at least be confident that the quality, quantity and location of appropriate habitat and representative ecosystems within catchments is of great importance [56]. It is also feasible to identify those wetland uses which are more or less sympathetic with catchment functions, providing a basis for the sustainable use of critical wetland areas [43]. For example, where orographic processes are significant in providing a source of water across catchment systems, the vitality of moist upland areas may be of fundamental importance to the hydrology of whole catchment systems (as for example in the Western Ghat mountains of Deccan India, the Pacific crest of the Andes in Amazonia, or the Drakensberg mountains as a key water capture area for South Africa.) Equally, wetland zones and naturally-inundated floodplain areas may be important for self-purification of water and flood detention in lower catchments [17,57]. These key areas of habitat provide not only nature conservation benefits but are also ultimately economically important through the various other beneficial services they produce to the advantage of wider constituencies throughout entire river catchments. The protection of

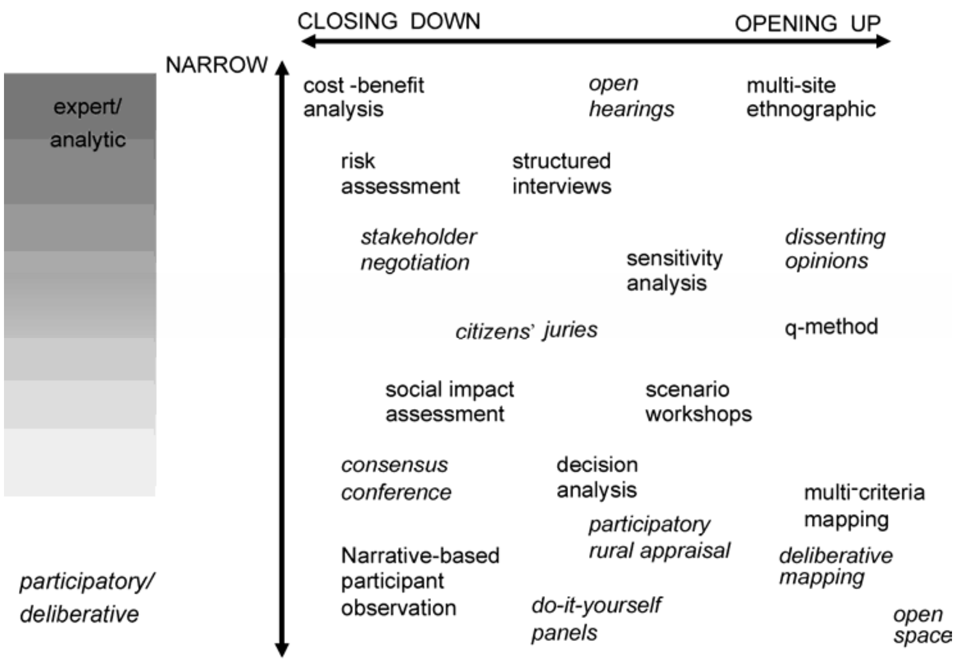

Figure 5. A schematic space for examining individual methods in appraisal design [54].

such important functional zones of catchments is therefore not a matter of altruism but represents a wise investment in the source of ecosystem services central to sustaining the diverse uses and values enjoyed by catchment communities [48].

There is a growing evidence base to substantiate the value of restoration of lost habitat critical for ecosystem functioning as a means to secure enduring benefits stemming from the supportive capacities of catchments [58]. Everard [47] reviews various schemes around the world wherein investment in restoration of critical catchment functioning has yielded economic and social benefits on a sustainable basis. This includes the famous Delaware-Catskills scheme in New York State and SCaMP in the north west of England. Although research questions remain to be answered, the cost-effective delivery of water savings within South African catchments, based upon clearance of water-hungry invasive vegetation, has been proven. (DWAF [59], and as reviewed by Woodworth [60]). An analysis of the mechanics and magnitude of water savings within South African catchments demonstrates that total incremental water use by invasive plants, controlled by the *Working for Water* initiative, account for as much as one-third of the estimated total water use in the Western Cape with the greatest percentage reduction in natural run-off a staggering 91% in the Namaqualand coast [61]. This is due largely to increased evaporative loss by invasive trees compared to native herbaceous vegetation [62] with rooting depth a key factor in depleting the water recharge of former rangelands [63]. In a study initiated to improve targeting of removal of problem species in the most impacted places, preliminary assessments of the costs, benefits and progress of South Africa's *Working for Water* programme demonstrate a considerable set of benefits associated with improved water yields [64,65] and additional benefits for further ecosystem services in other South African biomes [66]. However, one of *Working for Water*'s key strengths is its integration of ecological, economic and social goals, which have also delivered multiple additional benefits to society including employment and training for formerly excluded communities. The demonstrable success of the *Working for Water* programme is seen as influential in the decision by former US President Clinton to initiate the Comprehensive Everglades Restoration Program (www.evergladesplan.org), one of the largest natural capital restoration projects in the world. Related initiatives such as the Australian Landcare scheme (www.landcareaustralia.com.au), local projects set up by the UK's network of voluntary River Trusts (as reviewed by Everard [48]), and ecosystem service-related conservation in the catchment of Kenya's Lake Naivasha demonstrate the effectiveness of initiatives placing the functioning of catchment ecosystems at the centre of planning to improve hydrology, water quality and other functions delivering the beneficial services enjoyed by catchment communities. This feedback of societal consensus into protection or restoration of ecosystems and their services is illustrated at Figure 6.

Perspective 4 also becomes important in considering the resilience of catchments to environmental stresses, particularly in the light of increasing human demands and the stresses of climate change [67]. Ecosystem resilience was defined by Holling [68] as relating to the magnitude of disturbance that can be absorbed before a system changes its structure. Whilst the finer details of factors contributing to ecosystem resilience remain poorly understood, and there is even less consensus on how resilience is best measured, the integrity of ecosystems and their continued functioning is nonetheless perceived as a vital underpinning particularly in the light of growing environmental pressures [24]. The continuity of beneficial ecosystem services is therefore one of the key factors to be included within planning for resilient and sustainable catchments.

2.5. Perspective 5: Collective Visioning and Cooperative Governance

Rather than competing for finite and dwindling resources, shared understanding within catchment communities of the ecological basis for production of ecosystem services can provide a mechanism to promote social dialogue about a desired future. It is possible to go beyond collective bargaining about allocation of the remaining ecosystem services across catchment communities, moving instead towards mitigation or restoration to create capacity for current and future human needs. Desired catchment 'outputs' – services that deliver the uses and values enjoyed by society – may instead serve as a foundation for development of a collective vision of the future needs of the diverse constituencies within a shared catchment.

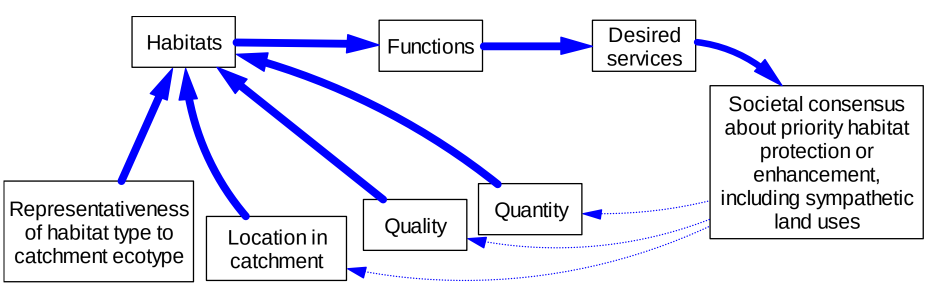

Figure 6. Protection or enhancement of catchment functions and services.

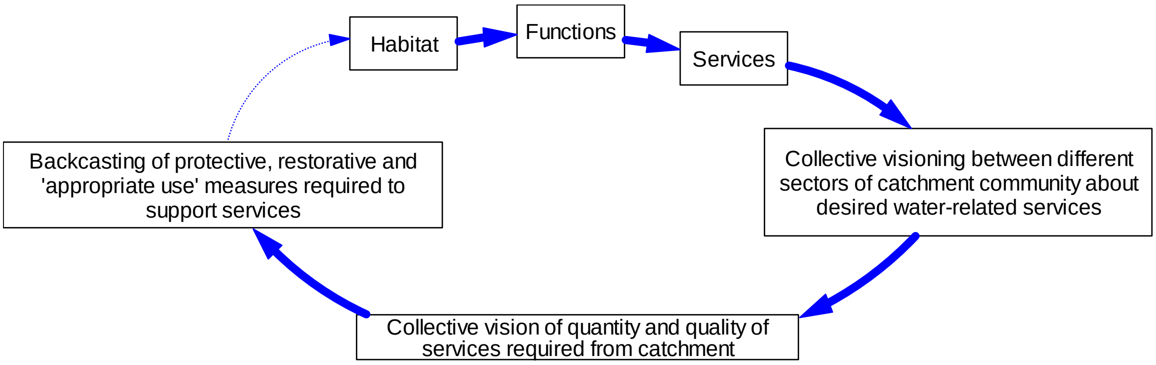

Figure 7. 'Desired future' value chain.

Where effective social dialogue can be brokered to reach agreement on a desired set of services to support the often-conflicting needs of all, catchment communities can then work 'upstream', back along the value chain, to determine the functions, and hence habitats, ecosystems and appropriate technological modifications, that can provide for them sustainably. This form of shared vision can relieve contention and conflict; indeed, cross-catchment agreements on water allocation and management can be a powerful focal point for promoting peace and overcoming historic conflicts particularly in water-stressed regions [69].

Backcasting is an effective means for achieving this, based not on the extrapolation of trends and predictable future events (i.e. 'forecasting') but instead taking as its reference point a clearly-articulated end-goal from which to work progressively towards identifying those policies, activities or trends that need to be adjusted to achieve a 'preferred' future [70]. For this to work, a common understanding is required of the underpinning sustainability principles that can lead to judgements about strategically important protection and restoration measures, and to identify the innovations that will be necessary to make 'step changes' and to found new social and economic agreements to make them work. By starting from the 'end-goal' perspective, backcasting can also help make sustainable development tractable, enabling the breaking down of sustainable development actions into 'bite-sized chunks' that lead towards a far longer-term result that is owned by catchment communities.

Running the value chain backwards, we can envisage diverse communities within a catchment getting together, for example under the aegis of a Catchment Management Agency, Water User Association or other (South African) stakeholder model, to identify the services required, the critical ecosystem functions that supply them, the productive ecosystems that these depend upon, and therefore the catchment characteristics required to support all stakeholders' needs. At this point, limitations of linear 'value chains' used in isolation begin to be exposed, with a need to join them up into cyclic systems if they are to stimulate iterative changes for progressive improvements to the wellbeing of people depending upon the diverse ecosystem services performed by catchments. This iterative investment in ecosystem-mediated collective wellbeing may best be achieved through a process of co-operative governance that matches the desired future with the habitats and functions that 'produce' the desired services. This is illustrated as Figure 7.

Such an approach is being trialled in practice in the Inkomati water management area (IWMA) in South Africa, where the Inkomati Catchment Management Agency (ICMA) has brought together diverse stakeholders during 2007 in order to create a vision for the future of the IWMA [35], using the 'Future Search' dialogue process [55]. The nine themes of the 'common ground' vision statement produced and agreed by stakeholders at the IWMA Future Search workshop held in the Inkomati catchment in October 2007 were as follows:

- All stakeholders actively working together – improved stakeholder co-operation
- Quality of river and ecosystems improved – less pollution – greater environmental awareness
- Equitable distribution of water to all stakeholders
- Improved infrastructure for water distribution
- Capacity and skills development – emerging farmers becoming commercially empowered
- Recognition of the role and importance of the ICMA
- Improved governance and compliance with legislation
- Improved gender balance
- Job creation though tourism

This provides a strategic and consensual framework for policy and management of the catchment to maximise the benefits to all sectors of the catchment community. The framework can be used as the basis for determining planning applications, instituting catchment protection measures, targeting of appropriate restoration initiatives (i.e. *Working for Water* or the partner *Working for Woodlands*, *Working on Fire* and *Working for Wet-*

lands schemes in South Africa, amongst other options, etc.), all of which can be cross-referenced and cost-justified on the basis of delivery of ecosystem services. Given the uncertainties in the trajectory of ecosystem restoration and the untested nature of this approach, this visioning and the strategy for its longer-term delivery will need to be based on the principles of adaptive management, embedded within a cooperative governance or social learning framework [67,71,53].

Ultimately, it will be necessary to embed these innovative management approaches within River Basin Management Plans and other statutory planning frameworks. This conclusion echoes that of [72] who, having co-developed an Integrated Management Plan (IMP) for the Alfeios basin (Greece) aimed at protecting or restoring surface water and groundwater through partnerships leading to agreed goals and solutions implementation processes, identified a need for the eventual lodgement of the IMP within Greek National Plans for water.

2.6. Towards an Integrated Model

Water and the supportive ecosystem services associated with it are, of course, not merely convenient human commodities but are the basis of one of the great life support cycles of this planet. The water cycle is infinitely renewable, with its cyclic nature one of the defining features of sustainability. Therefore, to think in terms just of 'value chains' is to assess water in fragmented and utilitarian rather than sustainable terms. 'Hard' engineering solutions have a role to play in securing access to water for populations of high density relative to natural environmental 'carrying capacity' in arid regions such as South Africa. 'Softer', ecosystem-focused solutions discussed in this paper have a key role in water policy to augment and add resilience to water supply. This may include not only directly serving the needs of dependent communities distributed within catchments but also helping maximise the longevity and hence value of pre-existing 'hard' infrastructure. Protection and enhancement of ecosystem functioning delivers multiple benefits on a sustainable basis, both in terms of local use and extending the social and economic values of dams, pipes and other durable infrastructure. To develop a sustainable relationship with water and its associated ecosystem services, society has to consider its 'value chains' not in linear isolation but within the context of this greater water cycle.

Furthermore, while it has become commonplace from a reductionist perspective to view the world through separate social, economic and ecological lenses, from a systemic perspective these dimensions are fully interdependent. Every element is intimately influenced by each other, just as decisions and actions taken by a sector of society in isolation from wider consideration of ecosystem functions will have ramifications for all others within catchment communities.

For this reason, sustainable thinking and decision-making depends upon the weaving of these socially-, economically- and ecologically-based value chains into a cohesive and integrated systems model. This will then provide a basis for thinking and acting that takes account of the interdependencies between each element, forming a basis upon which catchment communities can plan and manage collectively for an equitable, sustainable and efficient future.

Some work has already been undertaken to integrate some of these value chains. For example, the document *eThekwini Catchments: A Strategic Tool for Management* [73] is a practical development planning tool that embeds an 'ecosystem services' approach into urban planning, recognising that further economic development of the city of Durban and the greater eThikwini municipality (in KwaZulu-Natal, South Africa) is limited by the environmental carrying capacity of its river catchments. The document provides planners with a graphic and simple means to determine the likely impacts of development proposals on various beneficial ecosystem services upon which the wellbeing of people and economic activities depends, making clear the relevant costs, benefits and other implications for carrying capacity in any development planning decision. A study by South Africa's Institute of Natural Resources (INR) of economic impacts on ecosystem services in the Thukela (Tugela) river catchment [74] applies a variety of methods to ascribe economic values to the wide range of current uses enjoyed by the diverse communities within various of the river's sub-catchments. The study then proceeds to evaluate marginal changes to these benefits and disbenefits as affected by a set of Instream Flow Requirement (IFR) scenarios. This reveals a significant divergence of costs and benefits, in total and across affected communities, in the sub-catchments targeted by the study.

These studies are preliminary but extremely helpful in linking ecosystem functioning with the services, uses, values and societal implications of different options for development within planning, effectively linking Perspectives 1 to 3 within this study. The *Working for Water* programme makes a major contribution to Perspective 4. The study *Payment for Ecosystem Services: Developing an Ecosystem Services Trading Model for the Mnweni/Cathedral Peak and Eastern Cape Drakensberg Areas* [58] seeks to make linkages between the restoration and management of upper catchment areas for the purposes of increasing run-off of water, yielding economic benefits to catchment communities, for which it proposes a trading model to link the beneficiaries to the currently public investment in habitat management. Thereby, the Maloti Drakensberg Transfrontier Project study seeks to link an aspect of Perspective 5 (a vision of increased water availability from the upper catchment) with Perspectives 1 to 3.

Therefore, not only are the various value chains (represented here as 'Perspectives') understood and accepted, but there is already progress towards their integration. We propose a full integration of these disparate value chains as described into an integrated catchment value system, as illustrated below in Figure 8.

We appreciate that this model is evolving and that, in particular, the relationships illustrated by each arrow may not be well understood. Furthermore, given the difficulties inherent in predicting the trajectory of ecological restoration and the uncertainties in the methods, the model must be applied in an adaptive and contextualized manner.

However, these uncertainties should not be construed as a basis for delay with integration of social, economic and ecological elements of catchment planning around a nucleus of ecosystem services. It is already abundantly clear that, without restoration of catchment functions, the net capacity of catchment services is finite, and where natural limits are over-ridden then ecosystem services and catchment integrity will inevitably decline to the detriment of the majority of catchment communities. In a water-stressed world with a growing population and the looming threat of climate change, strategic planning and implementation of integrated water resource management is a pressing priority.

Adaptive decision-making will be required to reflect this interdependence of catchment ecosystem functions and services, reflecting the fact that human needs and uses as well as catchment condition, ecological response and climate change effects will fluctuate over time.

3. Discussion

The synthesis of ecologically-, economically- and socially-based value chains into an integrated catchment value system provides an over-arching framework for considering equity, sustainability and efficiency (the three driving principles of South Africa's National Water Act 1998 [34]) in practice. It does so not only by integrating these three themes but also by taking the finite supportive capacities of the catchment – the ecologically-based water value chain – as central to all other decisions. It thereby provides a practical basis for implementing the 'ecosystems approach' through a co-operative governance framework.

The sustainability and efficiency principles are transparent in the construction of the model, relating to balancing 'production' by the catchment ecosystem with use and sharing of water by the human population. The equity principle is also implicit within the model but is worthy of further commentary. It is in the dialogue around the integrated catchment value system that equity is enshrined in ensuing management decisions, ensuring that all sectors of catchment communities are facilitated in dialogue about a share of catchment services (Perspective 3), in the vision of catchment enhancement to maximise services (Perspective 5) and in the reward for land management to 'produce' the benefits enjoyed by others downstream as implicit in the integrated catchment value system as well as the Maloti Drakensberg Transfrontier Project [58] model. We also need to ensure an equitable distribution of management and other costs associated with modifying ecosystem services within catchments.

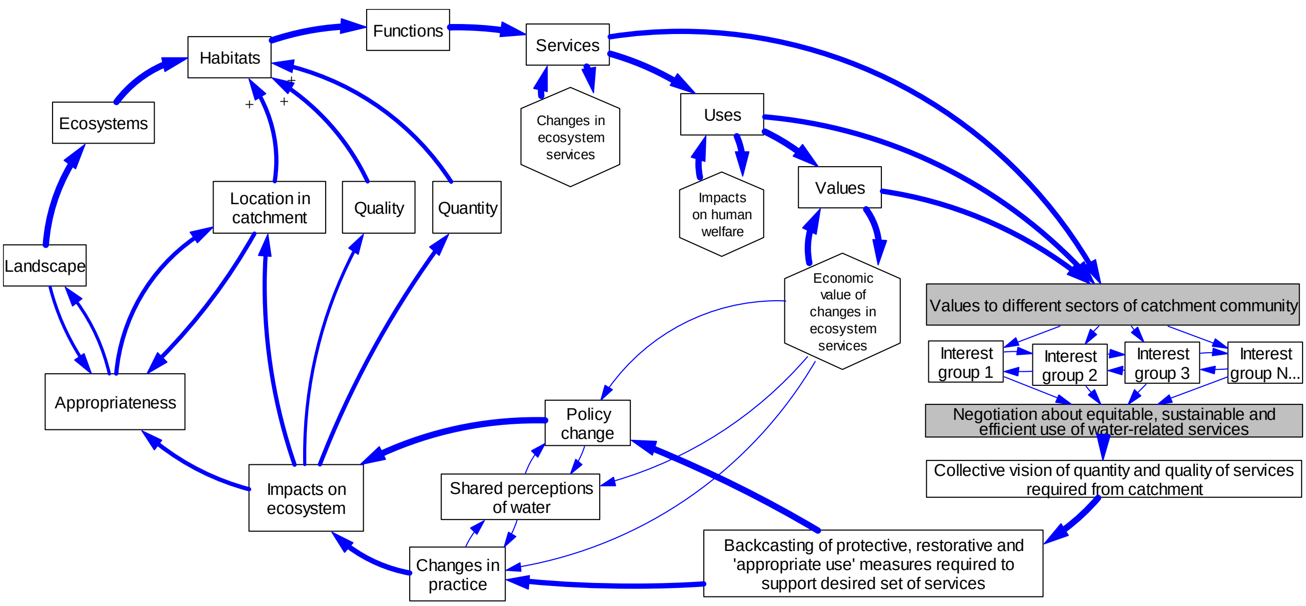

Figure 8. Towards an integrated value chain model.

It is above all important to emphasise that our work on this integrated catchment value system model arises through action research dialogue with catchment managers (staff of the ICMA and DWAF KZN (KwaZulu-Natal provincial office of the Department of Water Affairs and Forestry)), described by Colvin *et al*. [35]. This work is enabling us to develop a facilitation framework to guide practical decision-making about sustainable use of catchments. Fundamental principles of this framework are that it seeks equitable shares of access to water services and the distribution of costs, their sustainable exploitation, protection and restoration, and a basis for efficient and innovative uses that make room for all of the catchment community and the integrity of the ecosystems that 'produce' the beneficial services upon which they rely.

The model is also intended to help communicate to wider publics in catchment communities that investment in ecosystems (i.e. natural capital) is not competitive with human needs but rather provides the basis for quality of life. Catchments with diverse and representative habitats and associated ecosystem functions provide resilient and varied services supply just as, conversely, degraded catchments are compromised in their resilience and their capacity to support multiple human needs indefinitely. This has been demonstrated by improved water yields, water quality and biodiversity in landscapes managed favourably, including under South Africa's *Working for Water* and *Working for Wetlands* programmes amongst other examples, as well as through targeted agricultural improvements, more natural flow regimes instituted by sensitive water releases from dams, river habitat and wetland restoration, and a range of related measures implemented across the world.

Investment in appropriate ecosystem management and/or restoration can enhance catchment functioning, boost ecosystem services, increase societal use and utility, and deliver greater and more resilient value (both economic and subsistence) to the optimal benefit of catchment communities. All stakeholders have an interest in collaboration to protect or improve the core resource upon which their evolving and interdependent needs depend: the supportive capacities of catchment ecosystems.

If this integrated catchment value system model can be used as a basis for dialogue about allocation of ecosystem services benefits and costs, and visioning of a desired future, it may also make a contribution to 'ownership' of catchment management and societal cohesion amongst the many elements of the catchment community.

4. Acknowledgements

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5. References

[1] Ramsar Convention, "Convention on wetlands of international importance especially as waterfowl habitat," Ramsar, Iran., 1971.

[2] IUCN/UNEP/WWF, "World conservation strategy: living Resource conservation for sustainable development," IUCN, Switzerland: Gland, 1980.

[3] WCED, "Our common future," Oxford University Press, Oxford: England, 1987.

[4] J. Cock and E. Koch, "Going green: People, politics, and the environment in South Africa," Oxford University Press, Cape Town, 1991.

[5] W. Beinart and P. Coates, "Environment and history: The taming of nature in the USA and South Africa," Routledge, London, 1995.

[6] J. Mittelman, "Globalisation and environmental resistance politics," Third World Quarterly, Vol. 19, No.5, pp. 847–872, 1998.

[7] J. Cock, "Going green at the grassroots," In: J. Cock and E. Koch (Eds.) Going Green: People, Politics and the Environment, Oxford University Press, Cape Town, pp. 1–17, 1991.

[8] M. Castells, "The power of identity," Blackwell, London, 1997.

[9] S. R. Brechin, P. R. Wils–Husen, C. L. Fortwangler, and P. C. West, "Contested nature: Promoting international biodiversity with social justice in the twenty-First century," State University of New York, Albany, 2003.

[10] W. Crane, "Biodiversity conservation and land rights in South Africa: Whither the farm dwellers?" Geoforum, Vol. 37, No. 6, pp. 1035–1045, 2006.

[11] M. V. Melosi, "Equity, eco-racism and environmental history," Environmental History Review, doi: 10. 2307/ 3984909, Vol. 19, No. 3, pp. 1–16, 1995.

[12] C. Merchant, "American environmental history: An introduction." Columbia University Press, 2007.

[13] T. Jackson, material concerns, Routledge: London, 1996

[14] C. W. S. Dickens, "Obstacles to the implementation of environmental flows," Proceedings of the CAIWA (Conference on Adaptive and Integrated Water Management), Switzerland, Basel, 2007.

[15] R. Costanza, R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Haeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. van den Belt, "The value of the world's ecosystem services and natural capital," Nature, Vol. 387, pp. 253–260, 1997.

[16] G. C. Daily, "Nature's services: Societal dependence on natural ecosystems," Island Press, Washington DC, 1997.

[17] P. Denny, "Benefits and priorities for wetland conservation: The case for national wetland conservation strategies," In: M. Cox, V. Straker and D. Taylor (Eds), Proceedings of the International Conference on Wetlands Archaeology and Nature Conservation. HMSO, London, 1995.

[18] P. J. Dugan, "Wetland conservation: A review of current issues and required action." IUCN, Gland, Switzerland, pp. 96, 1990.

[19] E. Maltby, "Wetland goods and services – real values amid unreal economics?" In Driver, P. (Ed.) Harmonising Environmental Conservation and Economic Development. IUCN Special Publication, Gland: Switzerland, 1991.

[20] I. R. Calder, "The blue revolution: Land use and integrated water resources management," Earthscan Publications Ltd, London, 1999.

[21] S. J. Hall, "The effects of fishing on marine ecosystems and communities," Blackwell Science Ltd, Oxford, 1999.

[22] D. J. Krieger, "Economic value of forest ecosystem service: A review," The Wilderness Society, Washington DC, pp. 31, 2001.

[23] World Resources Institute, The World Conservation Union (IUCN) and United Nations Environment Programme, "Global biodiversity strategy: Guidelines for action to save, study, and use earth's biotic wealth sustainably and equitably," World Resources Institute: Washington, 1992.

[24] MA. "Millennium ecosystem assessment," *www. maweb. org.* 2004.

[25] Defra, "An introductory guide to valuing ecosystem services," Department for Environment, Food and Rural Areas, London, 2007a.

[26] Defra, "Securing a healthy natural environment: An action plan for embedding an ecosystems approach," Department for Environment, Food and Rural Areas, London, 2007b.

[27] R. de Groot, M. A. Wilson, and R. M. Boumans, "A typology for the classification, description and valuation of ecosystem functions, goods and services," Ecological Economics, Vol. 41, pp. 393–408, 2002.

[28] P. Johnston, M. Everard, D. Santillo, and K-H Robèrt, "Commentaries: Reclaiming the definition of sustainability," Environmental Science and Pollution Research, Vol. 14, No. 1, pp. 60–66. 2007.

[29] J. Porritt, "Capitalism as if the World Matters," Earthscan, London, pp. 336, 2005.

[30] W. D. Newmark, J. L. Hough, "Conserving wildlife in Africa: Integrated conservation and development projects and beyond". BioScience, Vol. 50, No.7, pp. 585–592, 2000.

[31] M. Everard and A. Powell, "Rivers as living systems," Aquatic Conservation, Vol. 12, pp. 329–337, 2002.

[32] M. Everard, "Investing in sustainable catchments," The Science of the Total Environment, Vol. 324, pp. 1–24, 2004.

[33] Ramsar Convention, "The Ramsar 25th Anniversary Statement " Resolution VI.14, 6th Meeting of the Conference of the Contracting Parties, Brisbane, March 1996.

[34] Republic of South Africa, "National Water Act. Act No. 36 of 1998," Government Gazette, South Africa, 1998.

[35] J. D. Colvin, F. Ballim, S. Chimbuya, M. Everard, J. Goss, G. Klarenberg, S. Ndlovu, D. Ncala, and D. Weston, "Building capacity for co-operative governance as a basis for integrated water resources managing in the Inkomati and Mvoti catchments," South Africa, Water SA, Vol. 34, No. 6, pp. 681-690, 2009.

[36] M. E. Porter, "Competitive advantage," The Free Press, New York, 1985.

[37] P. McCully, "Silenced rivers." Zed Books: London, 1996.

[38] F. Pearce, "Keepers of the spring: Reclaiming our water in an age of globalization," Island Press, Washington, pp. 260, 2004.

[39] G. C. Daily, T. Söderqvist, S. Aniyar, K. Arrow, P. Dasgupta, P. R. Ehrlich, C. Folke, A. Jansson, B-O. Jansson, N. Kautsky, S. Levin, J. Lubchenco, K-G. Mäler, D. Simpson, D. Starrett, D. Tilman, and B. Walker, "The value of nature and the nature of value," Science, Vol. 289, pp. 395–396, 2000.

[40] P. J. Boon, J. Wilkinson, and J. Martin, "The application of SERCON (system for evaluating rivers for conservation) to a selection of rivers in Britain," Aquatic Conservation: Marine and Freshwater Ecosystems, Vol. 8, No. 4, pp. 597–616, 1998.

[41] M. Everard, "Development of a British wetland strategy," Aquatic Conservation, Vol. 7, pp. 223-238, 1997.

[42] P. J. Raven, N. T. H. Holmes, F. H. Dawson, and M. Everard, Quality assessment using River Habitat Survey data," Aquatic Conservation, Vol. 8, pp. 477–499, 1998.

[43] M. Everard, P. Denny, and C. Croucher, "SWAMP: A knowledge-based system for the dissemination of sustainable development expertise to the developing world," Aquatic Conservation, Vol. 5, No. 4, pp. 261–275, 1995.

[44] IIED, "Water ecosystem services and poverty reduction under climate change," International Institute for Environment and Development: London, pp. 33, 2007.

[45] M. Everard, "Water quality objectives as a tool for managing sustainability," Freshwater Forum, Vol. 4, No. 3, pp. 179–189, 1994.

[46] H-P. Piorr, "Environmental policy, agri-environmental indicators and landscape indicators," Agriculture, Ecosystems and Environment, Vol. 98, pp. 17–33, 2003.

[47] M. Everard, "The business of biodiversity," WIT Press, Ashurst, England, 2009.

[48] M. Everard, W. Kenmir, C. Walters, and E. Holt, "Upland hill farming for water, wildlife and food," Freshwater Forum, Vol. 21, pp. 48–73, 2004.

[49] Ison, R.; Röling, N. and Watson, D. 2007. Challenges to science and society in the sustainable management and use of water: investigating the role of social learning. Environmental Science and Policy, 10: 499-511.

[50] World Commission on Dams, "Dams and development: A new framework for decision-making," Earthscan Publications Ltd: London, 2000.

[51] M. Makaulule, and H. Swamby, "African spirit," Resurgence, Vol. 247, pp. 28–29, March/April 2008.

[52] S. Stagl, "Rapid research and evidence review on emerging methods for sustainability valuation and appraisal," Final Report to the Sustainable Development Research Network (UK), January 2007.

[53] P. Steyaert and J. Jiggins, "Governance of complex environmental situations through social learning: A synthesis of SLIM's lessons for research, policy and practice," Environmental Science and Policy, Vol. 10, No. 6, pp. 575–586, 2007.

[54] A. Stirling, M. Leach, L. Mehta, I. Scoones, A. Smith, S. Stagl, and J. Thompson, "Empowering designs: Towards more progressive appraisal of sustainability," STEPS Working Paper 3, Brighton: STEPS Centre, 2007.

[55] M. Weisbord and S. Janoff, "Future search: An action guide to finding common ground in organizations and communities (Second Edition)," Berrett-Koehler: San Francisco, 2000.

[56] J. A. Drake, H. A. Mooney, F. Di Castri, R. H. Groves, F. J. Kruger, M. Rejmánek, and M. Williamson, "Biological invasions: A global perspective," Wiley, Chichester, 1989.

[57] P. Denny, "Gaia's kidneys: Wetlands are our life-blood," International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE), Delft, 1996.

[58] Maloti Drakensberg Transfrontier Project, "Payment for ecosystem services: Developing an ecosystem services trading model for the mnweni/cathedral peak and eastern cape drakensberg areas," Mander, M. (Ed.) INR Report IR281. Development Bank of Southern Africa, Department of Water Affairs and Forestry, Department of Environment Affairs and Tourism, Ezemvelo KZN Wildlife, South Africa, 2007.

[59] DWAF, "Working for water programme: Annual report 1996/97," Department for Water Affairs and Forestry, Pretoria, 1997.

[60] P. Woodworth, "Working for water in South Africa: Saving the world on a single budget?" World Policy Journal, pp. 31–43, Summer 2006.

[61] D. C. Le Maitre, D. B. Versfeld and R. A. Chapman, The impact of invading alien plants on surface water resources in South Africa: A preliminary assessment, Water SA, Vol.26, No. 3, pp. 397–408, 2000.

[62] P. J. Dye, and C. Jarmain, "Water use by Black Wattle (Acacia mearnsii): Implications for the link between removal of invading trees and catchment streamflow response," South African Journal of Science, Vol. 100, pp. 40–44, 2004.

[63] M. S. Seyfried and B. P. Wilcox, "Soil water storage and rooting depth: Key factors controlling recharge on rangelands," Hydrological Processes, Vol. 20, pp. 3261–3275, 2006.

[64] C. Marais and B. W. van Wilgen, "The clearing of invasive alien plants in South Africa: A preliminary assessment of costs and progress," South African Journal of Science, Vol. 100, pp. 97–103, 2004.

[65] J. K. Turpie, C. Marais, and J. N. Blignaut, "The working for water programme: Evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa," Ecological Economics, Vol. 65, No.4, pp. 788–798, 2008.

[66] B. W. van Wilgen, B. Reyers, D. C. Le Maitre, D. M. Richardson, and L. Schonegevel, "A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa," Journal of Environmental Management, Vol. 89, No. 4, pp. 336–349. (doi:10.1016/j.jenvman.2007.06.015.), 2008.

[67] V. R. Galaz, "Does the EC water framework directive build resilience? Harnessing socio-ecological complexity in European water management," Swedish Water House, Stockholm, 2006.

[68] C. S. Holling, "Resilience and stability of ecological systems," Annual Review of Ecology and Systematics, Vol. 4, pp. 1–23, 1973.

[69] A. Turton, "A critical assessment of the basins at risk in the Southern African hydropolitical complex," CSIR Report Number: ENV–P–CONF 2005–0001, CSIR: Johannesburg, 2005.

[70] J. Holmberg, and K. H. Robèrt, "Backcasting — A framework for strategic planning," International Journal of Sustainable Development and World Ecology, Vol. 7, pp. 291–308, 2000.

[71] C. S. Holling (Ed.), "Adaptive environmental assessment and management," Wiley: Chichester, 1978.

[72] I. D. Manariotis and P. C. Yannopoulos, "Adverse effects on Alfeios River basin and an integrated management framework based on sustainability," Environmental Management, Vol. 34, No. 2, pp. 261–269, 2004.

[73] N. Diederichs, T. Markewicz, M. Mander, A. Martens, and S. Zama Ngubane, "eThekwini catchments: A strategic tool for management, First Draft," eThekwini Municipality, KwaZulu-Natal, South Africa, 2002.

[74] M. Mander, "Thukela water project: Reserve determination module. Part 1. IFR scenarios in the Thukela River catchment: Economic impacts on ecosystem services" Institute of Natural Resources, Scottsville, 2003.

J. Water Resource and Protection, 2009, 3, 188-194
doi:10.4236/jwarp.2009.13023 Published Online September 2009 (http://www.SciRP.org/journal/jwarp/).

Influence Factors Analysis to Chlorophyll *a* of Spring Algal Bloom in Xiangxi Bay of Three Gorges Reservoir

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Abstract

To study the relationship between environmental variables and chlorophyll *a* of spring algal bloom in Xiangxi Bay of Three Gorges Reservoir, stepwise multiple binomial regression and grey relative analysis methods were adopted. In surveys, 13 stations have been investigated and 143 samples were collected weekly from March 4 to May 13 in 2007. The study shows environmental variables (turbidity, total nitrogen, dissolved oxygen, total phosphates and silicate) are key factors during algal bloom. The grey relative values and their permutation indicated that turbidity was the most important factor and had comprehensive effect on chlorophyll *a*. The more number of interactive variables is found to be an indication of biochemical activity during spring algal bloom in Xiangxi Bay such as DO×TN, Turb×TP and so on. There was good linear relationship between chlorophyll a and the interaction of DO with TN ($R = 0.9192$, $P = 0.0001$).The interaction of nutrients (TP×TN, TP×SiO_4, TN×SiO_4) had significant influence to chlorophyll *a* and probably determined the inter-specific competition at different nutrient concentrations.

Keywords: Stepwise Multiple Binomial Regression, Grey Relative Analysis, Chlorophyll *a*, Environment Variables, Algal Bloom, Xiangxi Bay

1. Introduction

Biomass of phytoplankton in terms of the concentration of chlorophyll *a* is one of the most widely accepted methods in the study of biological production as it indicates total plant material available in the water at primary level of food chain [1]. Hence the growing and declining condition of algal bloom can be described by the spatial and temporal variation of chlorophyll *a*. There are many study methods to the relationship between chlorophyll *a* and physicochemical factors such as stepwise multiple regression analysis [2], grey relative analysis [3] and artificial neural network [4]. Chlorophyll *a* can be related to the environmental parameters by means of linear regression, though it provides only the prediction efficiency of a single factor at a time [5–7]. But the algal bloom is the multivariate interaction and nonlinear process. So a number of factors jointly controlling the bioactivities are to be considered.

Grey theory can reflect the dynamic state of data and has been broadly applied in the last decade since Deng Julong suggested the division of systems information to white, grey and black [8]. The systematic analytical method of grey theory was used to study the relationship between biomass of *Noctiluca scientillans* Macartney or *Prorocentrum sigmoides* Bohm (two red tide organisms) and various physicochemical factors of seawater [9,10].

Recently the relationship between chlorophyll *a* and environmental factors in Xiangxi Bay of Three Gorges Reservoir form March to April in 2005 were reported [6]. They showed that ecological factors (including total nitrogen, total phosphorus, water temperature, transparency and dissolved oxygen) had significant impact on the concentration of chlorophyll *a* using correlation analysis and linear regression method. But the multivariate interaction and nonlinear process in the algal bloom were not considered in the previous work. So this present paper aims to study: (1) controlling and interactive factors of chlorophyll *a*, (2) nonlinear interrelationship between physicochemical parameters and chlorophyll *a* of spring algal bloom in Xiangxi Bay. In order to achieve this, stepwise multiple binomial regression method and grey relative analysis are adopted.

2. Materials and Methods

2.1. Area Description

The Three-Gorge Dam (TGD) in China is the world's largest dam, measuring 2335 m long and 185 m high, and the reservoir created by it will have an area of 1080 km^2 in 2009 [11]. The Xiangxi River, which lies 38 km upstream from the Dam, is the largest tributary in the Hubei portion of Three-Gorge Reservoir (TGR). This river is 94 km long with a watershed of 3099 km^2 (between 110°25′and 111°06′E long., 30°57′and 31°34′N lat.) [12]. With impoundment of TGR, the downriver stretch of Xiangxi River was inundated and Xiangxi Bay was formed. The water level in the Xiangxi River has increased 40 m and the water flow velocity has dropped from the original 0.43-0.92 m/s [13] to 0.0020-0.0041 m/s [14]. So when water temperature increased in spring, there were algal blooms with prolonged retention time and high nutrient concentrations in Xiangxi Bay. *A. Formosa*, *C. acuta* and *C. ovata* were the dominant species.

2.2. Sampling and Analysis

Water samples were collected at 13 stations in Xiangxi Bay (Figure 1). Stations X0-X11 are on the Xiangxi River. Station GL is located at the downstream of Gaolan River, which is the largest tributary of the Xiangxi River. Samplings were performed weekly from March 4 to May 13, 2007. Water samples were collected at 0.5 m depth from surface in the middle of the river using a 5-L Niskin sampler (Hydrobios-Kiel). Water temperature (WT), dissolved oxygen (DO), pH, turbidity (Turb) were recorded in situ using multi-parameter water quality analyzer (Hydrolab DS5). Total phosphates (TP), phosphate (PO_4), total nitrogen (TN), ammonium nitrogen (NH_4), nitrate (NO_3), silicate (SiO_4) were determined in the laboratory using State Environmental Protection Administration (SEPA) standard methods [15]. For chlorophyll *a* (Chl.*a*) analysis, samples filtered through Whatman GF/F filters were extracted with cold 90% acetone and estimated by spectrophotometer [16].

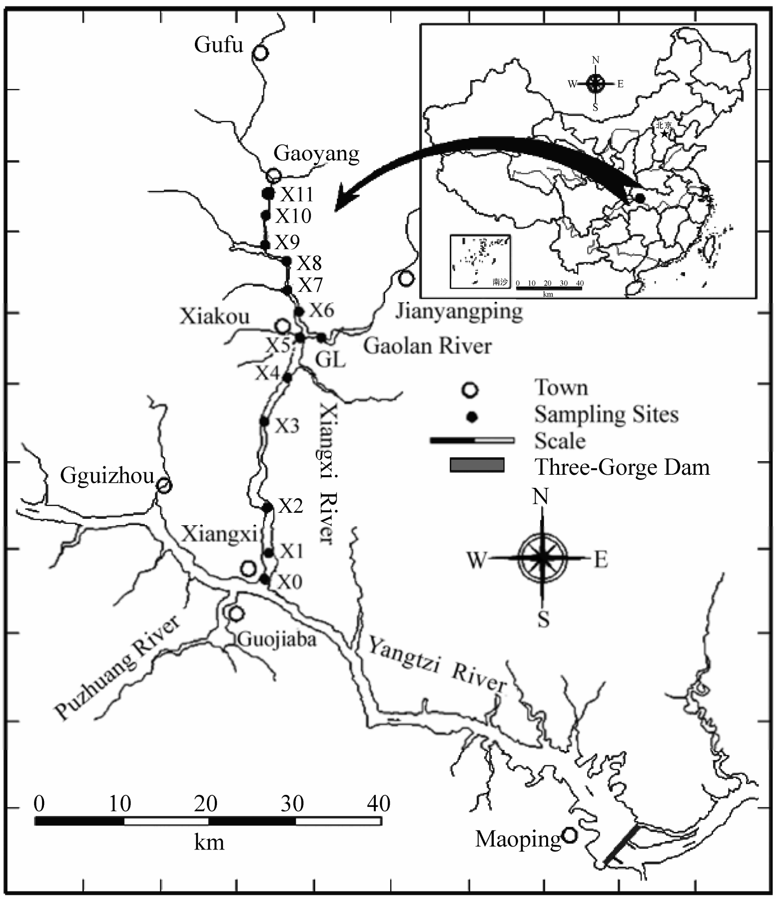

Figure 1. Sampling stations in Xiangxi Bay.

2.3. Statistical Analysis Using Stepwise Multiple Regression

Method of choosing the minimal set of environmental variables that can explain the variation in the affected parameter [17] was adopted earlier. A modern approach to explore the possible influence of various environmental variables on phytoplankton dynamics is the application of a multivariate statistical analysis [18]. These methods are widely used in ecological studies and have proved to be useful for understanding interactions between ecological factors that influence phytoplankton production. In this study, an attempt is made to include the individual factors, second order and interaction effects of the environmental parameters viz: WT (℃), DO (mg/L), pH, Turb (NTU), TP (mg/L), PO_4 (mg/L), TN (mg/L), NH_4 (mg/L), NO_3 (mg/L) and SiO_4 (mg/L) to relate chlorophyll *a* concentration (mg/m^3) in the predictive model. A stepwise multiple regression analysis is applied using phytoplankton (Chl.*a*) as the dependent variable, while individual, second order and interaction effects of the above listed environmental parameters as the independent variables, to examine the controlling role of any particular parameter or group of parameters on phytoplankton biomass.

2.4. Grey Relative Analysis

Based on the above investigation, chlorophyll *a* concentration (mg/m^3) in Xiangxi Bay was used as the analyzed sequence $\{X_0(k)|k=1,2,\cdots,N\}$, where sampling number $N=143$, and 10 factors including WT (℃), DO (mg/L), pH, Turb (NTU), TP (mg/L), PO_4 (mg/L), TN (mg/L), NH_4 (mg/L), NO_3 (mg/L) and SiO_4 (mg/L) were to be regarded as comparative sequences or subsequences $\{X_j(k)|k=1,2,\cdots,N\}$ $(j=1,2,\cdots,10)$. The calculation method [19] of grey system relative degree is as follows:

All the sequences are initiated for making them comparable. Let the analyzed sequence be:

$$\{Y_0(k)|k=1,2,\cdots,N\}=\{Y_0(1),Y_0(2),\cdots,Y_0(N)\}=\left\{\frac{X_0(1)}{M_0},\frac{X_0(2)}{M_0},\cdots,\frac{X_0(N)}{M_0}\right\} \quad \textbf{(1)}$$

where $M_0=\frac{1}{N}\sum_{k=1}^{N}X_0(k)$

So the comparative sequences are:

$$\{Y_j(k)|k=1,2,\cdots,N\}=\{X_j(k)/M_j|k=1,2,\cdots,N\}(j=1,2,\cdots,10) \quad \textbf{(2)}$$

where $M_j=\frac{1}{N}\sum_{k=1}^{N}X_j(k)$

Let $\zeta_i=\{\zeta_i(k)|k=1,2,\cdots,N\}(i=1,2,\cdots,10)$ be a relative coefficient between the analyzed sequence $\{Y_0(t)\}$ and the comparative sequence $\{Y_j(t)\}$, which is called the grey relative coefficients. Then

$$\zeta_i(k)=\frac{\underset{k}{Min}\Delta_i(k)+\underset{k}{Max}\Delta_i(k)}{\Delta_i(k)+\rho\underset{k}{Max}\Delta_i(k)} \quad (i=1,2,\cdots,10;k=1,2,\cdots,N) \quad \textbf{(3)}$$

where $\Delta_i(k)=|Y_0(k)-Y_i(k)|$ and $\rho(0<\rho<1)$ is a distinguished coefficient. Here we take it as $\rho=0.1$. Let

$$\gamma_i=\frac{1}{N}\sum_{k=1}^{N}\zeta_i(k) \qquad (i=1,2,\cdots,10) \quad \textbf{(4)}$$

where γ_i is a relative degree between the analyzed sequence $\{Y_0(t)\}$ and the comparative sequence $\{Y_j(t)\}$.

3. Results

Using stepwise multiple binomial regression method, the "optimal" empirical mode of multiple binomial regression to chlorophyll *a* of spring algal bloom in Xiangxi Bay is obtained as follows:

$$Chl.a=40.1878-12.5897DO+0.5767(DO)^2+3.2052DO\times TN-1.2818Turb\times TP-58.9301TP\times TN+34.9789TP\times SiO_4-3.9612TN\times SiO_4$$
$$(R=0.7780,\ S=14.8202,\ F_{7,135}=29.5654,\ P=0.0001,\ n=143) \quad \textbf{(5)}$$

Partial correlation coefficient, t test value and p-value of independent variables in Equation (5) are presented in Table 1. All p-value of independent variables are less than 0.05.

The grey relative values between the analyzed sequence and subsequences for samples of 13 stations were calculated. The results of relative values are listed in Table 2, and the results of their permutation are in Table 3.

4. Discussion

The stepwise multiple regression and grey relative analysis show the environmental variables (Turb, TN, DO, TP, SiO_4) are more important and can reflect the

Table 1. Partial correlation coefficient, t test value and p-value of independent variables in Equation 5.

independent variables	partial correlation coefficient	t test value	p-value
DO	-0.5510	7.6714	0.0001
$(DO)^2$	0.6519	9.9881	0.0001
DO×TN	0.3521	4.3705	0.0001
Turb×TP	-0.2051	2.4342	0.0162
TP×TN	-0.2239	2.6698	0.0085
TP×SiO_4	0.4127	5.2644	0.0001
TN×SiO_4	-0.2720	3.2847	0.0013

Table 2. Grey relative values between chlorophyll *a* and physicochemical factors.

Station	WT	DO	pH	Turb	TP	PO_4	TN	NH_4	NO_3	SiO_4
X0	0.3512	0.3461	0.3351	0.3434	0.3663	0.3450	0.3942	0.3587	0.3289	0.3211
X1	0.4094	0.4540	0.4107	0.4859	0.4917	0.4151	0.4317	0.4293	0.4259	0.4510
X2	0.5068	0.5144	0.5198	0.5808	0.5435	0.5179	0.5115	0.4953	0.4853	0.5288
X3	0.3985	0.4413	0.3921	0.4173	0.3826	0.3570	0.4216	0.3717	0.3692	0.4032
X4	0.4395	0.4843	0.4415	0.4440	0.4034	0.4071	0.4702	0.4044	0.4375	0.4551
X5	0.4923	0.4948	0.4996	0.5399	0.4995	0.4827	0.5304	0.4612	0.5109	0.5188
GL	0.3717	0.4189	0.3403	0.3754	0.3935	0.3781	0.3497	0.3568	0.3541	0.3582
X6	0.3556	0.4084	0.3472	0.3997	0.3921	0.3936	0.4077	0.3449	0.3524	0.3574
X7	0.3963	0.3936	0.4036	0.4073	0.3662	0.3409	0.4640	0.3448	0.3422	0.3749
X8	0.4096	0.4454	0.4045	0.4503	0.4545	0.4476	0.4139	0.4050	0.4037	0.4262
X9	0.4265	0.3819	0.4578	0.4045	0.4213	0.3977	0.4399	0.3629	0.3750	0.4445
X10	0.4007	0.3861	0.4374	0.3825	0.4006	0.4084	0.3808	0.3817	0.3528	0.3792
X11	0.3592	0.3394	0.3779	0.3825	0.3867	0.3757	0.3686	0.4027	0.3976	0.3530

Table 3. Averages and permutation of the grey relative values from 13 stations.

	WT	DO	pH	Turb	TP	PO_4	TN	NH_4	NO_3	SiO_4
Average	0.4090	0.4237	0.4129	0.4318	0.4232	0.4051	0.4296	0.3938	0.3950	0.4132
Permutation	7	3	6	1	4	8	2	10	9	5

change of chlorophyll *a* concentration of spring algal bloom in Xiangxi Bay.

Based on grey relative analysis, Turbidity was the most important factor in the algal bloom and had comprehensive effect on chlorophyll a. As the low turbidity value chlorophyll *a* was in high level (Figure 2) because light illuminance under clear water was high and beneficial to phytoplankton photosynthesis [20]. When it rained from April 15 to April 22 in Xiangxi Bay, turbidity and silt increased, light illuminance under water decreased. Meanwhile, nutrients such as phosphates were adsorbed by silt in the river (interactive factor Turb×TP was included in Equation 5). So algal bloom declined.

Nitrogen entering aquatic systems arises from a variety of sources that include point and non point source pollution, biological fixation of gaseous nitrogen and the deposition of nitrogen oxides and ammonium [21]. Mean TN of spring algal bloom in Xiangxi Bay was 1.1289 ± 0.4175 mg/L with a minimum and maximum concentration of 0.3170 and 2.7890 mg/L respectively. Chlorophyll *a* of spring algal bloom had significant negative correlation with TN (Spearman $r = -0.18$, $n = 143$, $p < 0.05$), NO_3 (Spearman $r = -0.28$, $n = 143$, $p < 0.01$). Meanwhile TN had significant negative correlation with DO (Spearman $r = -0.32$, $n = 143$, $p < 0.01$) and there was good linear relationship between chlorophyll *a* and the interaction of DO with TN (DO×TN) (Figure 3):

$$Chl.a = 0.062721 + 1.014050(DO \times TN)$$

$$(R = 0.9192,\ S = 9.0913,\ P = 0.0001,\ n = 143) \quad \textbf{(6)}$$

These data indicate nitrogen transformation by DO

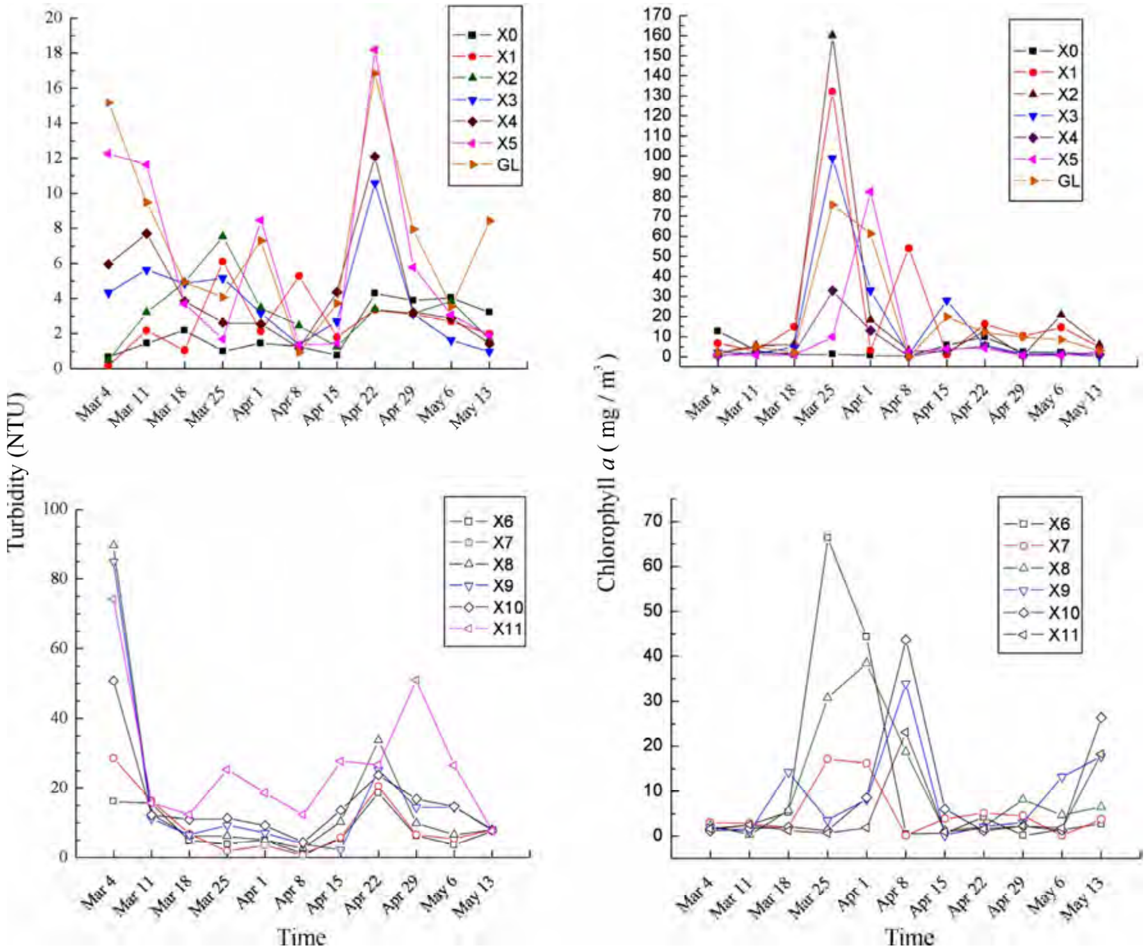

Figure 2. Temporal and spatial change of turbidity and Chl.*a* in different sampling stations of Xiangxi Bay.

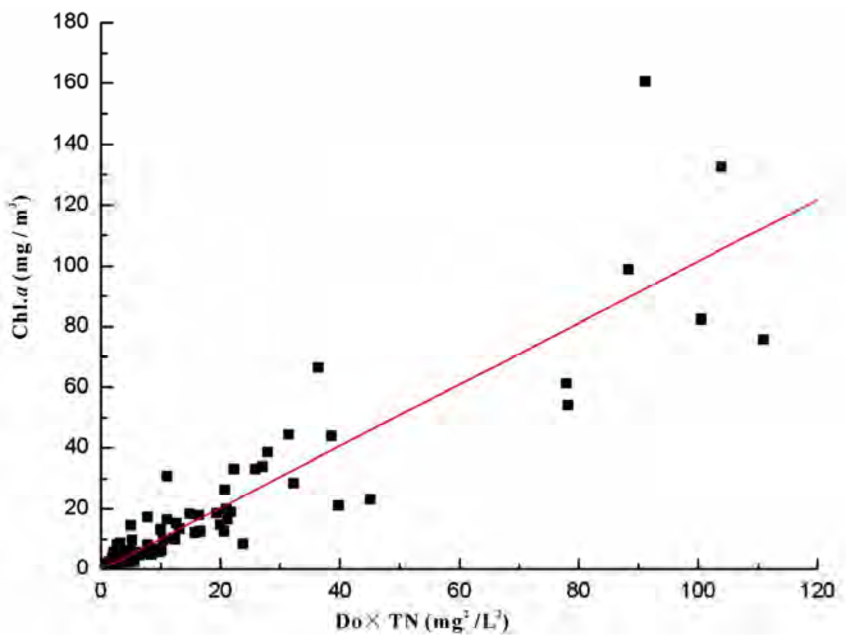

Figure 3. The relationship between chlorophyll *a* and DO×TN in Xiangxi Bay.

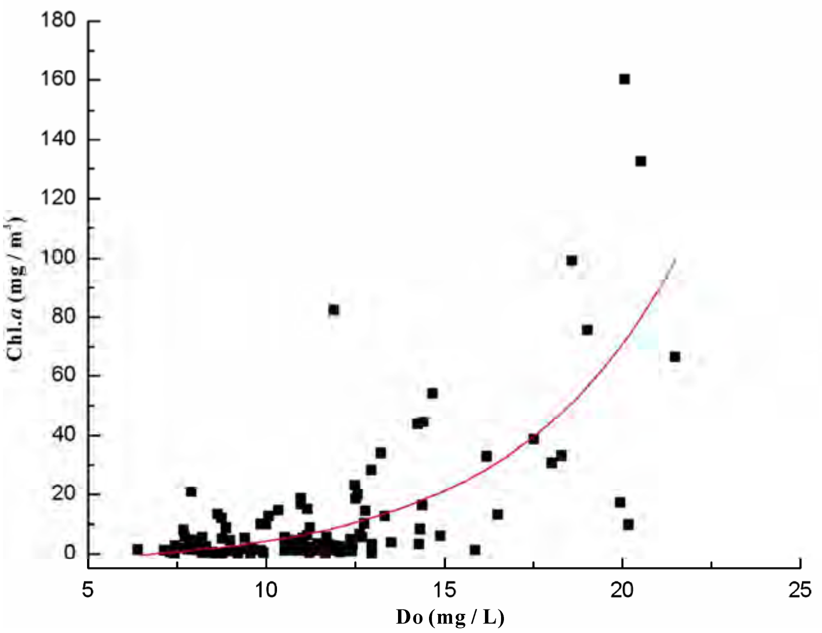

Figure 4. The relationship between chlorophyll *a* and dissolved oxygen in Xiangxi Bay.

plays an important role in phytoplankton growth and the soluble nutrients may be effectively uptake by phytoplankton.

The relationship between chlorophyll *a* and dissolved oxygen was nonlinear (Figure 4), which regression model was as follows:

$$Chl.a = -4.1969 + 0.9856\exp(0.2166DO)$$

$$(R = 0.7141,\ S = 16.1750,\ P = 0.0001,\ n = 143) \quad \mathbf{(7)}$$

It was due to the increase of oxygen which was released during phytoplankton photosynthesis [22] and the decrease of oxygen which was consumed by organic matter [23].

Total phosphate and silicate were also important factors to chlorophyll *a*. Mean values of TP and SiO_4 in Xiangxi Bay were 0.1958 ± 0.1095 mg/L and 3.7313 ± 1.0258 mg/L respectively during spring algal bloom. The phosphate load was high and increased from downstream to upstream because there were phosphate mines and phosphate plants in the upstream of Xiangxi River [24]. Diatoms were the dominant species during the later stage of algal bloom and silicate was necessary to diatoms growth. The cooperate interaction of nutrients (TP×TN, TP×SiO_4, TN×SiO_4) had significant influence to chlorophyll *a* during spring algal bloom based on stepwise multiple binomial regression and probably determined the inter-specific competition at different nutrient concentrations, because their intakes were species specific [25]. So the relationship between different algal species densities and different nutrient concentrations would be studied in the future work.

5. Conclusions

The study using stepwise multiple regression and grey relative analysis method shows the significant influence of environmental variables (turbidity, total nitrogen, dissolved oxygen, total phosphates and silicate) and their interactions on the production of chlorophyll *a*. The grey relative values and their permutation indicated that turbidity was the most important factor and had comprehensive effect on chlorophyll *a*. The more number of interactive variables is found to be an indication of biochemical activity during spring algal bloom in Xiangxi Bay such as DO×TN, Turb×TP and so on. There was good linear relationship between chlorophyll *a* and the interaction of DO with TN (DO×TN). The interaction of nutrients (TP×TN, TP×SiO_4, TN×SiO_4) had significant influence to chlorophyll *a* and probably determined the inter-specific competition at different nutrient concentrations.

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7. References

[1] G. A. Weyhenmeyer, T. Blenckner, and K. Pettersson, "Changes of the plankton spring outburst related to the

North Atlantic Oscillation [J],” Limnol Oceanogr, No. 47, pp. 1788–1792, 1999.

[2] K. K. Balachandran, K. V. Jayalakshmy, C. M. Laluraj, *et al*. “Step-up multiple regression model to compute Chlorophyll *a* in the coastal waters off Cochin, southwest coast of India [J],” Environ Monit Assess, No. 139, pp. 217–226, 2008.

[3] W. J. Huang, G. H. Huang, T. J. Jiang, *et al*. “Analysis of grey incidence of chlorophyll (a,b,c) and ecology factor in Dapeng Bay, South China sea [J],” Acta Oceanol Sin, Vol. 22, No. 1, pp. 136–139, 2000. [in Chinese]

[4] M. Xu, G. M. Zeng, X. Y. Xu, G. H. Huang, *et al*. “Application of Bayesian regularized BP neural network model for analysis of aquatic ecological data—A case study of chlorophyll *a* prediction in Nanzui water area of Dongting Lake [J],” J Environ Sci, Vol. 17, No. 6, pp. 946–952, 2005.

[5] Z. S. Liu, C. S. Wang, J. Y. Ni, *et al*. “Ecological distribution characteristics of chlorophyll a in Fuxian Lake [J],” Acta Ecologica Sinica, Vol. 23, No. 9, pp. 1773–1780, 2003. [in Chinese]

[6] X. Q. Han, L. Ye, Y. Y. Xu, *et al*. “Analysis of the spatial and temporal changes of chlorophyll a concentration in Xiangxi Bay in spring and its impact factors [J],” Acta Hydrobiologica Sinica, Vol. 30, No. 1, pp. 89–93, 2006. [in Chinese]

[7] X. L. Wang, Y. L. Lu, G. Z. He, *et al*. “Exploration of relationships between phytoplankton biomass and related environmental variables using multivariate statistic analysis in a eutrophic shallow lake: A 5–year study [J],” J Environ Sci, Vol.19, No. 8, pp. 920–927, 2007.

[8] J. L. Deng, “Introduction to grey system theory [J],” J Grey System, No.1, pp. 1–24, 1989.

[9] W. J. Huang and Y. Z. Qi, “Analysis of grey models between the environmental essential parameters of seawater and the growth of *Prorocentrum sigmoides* Bohm in Dapeng Bay, South China Sea [J],” Marine Environ Sci, Vol. 18, No. 1, pp. 45–49, 1999. [in Chinese]

[10] W. J. Huang, “Analysis of grey model between seawater environmental factors and growth of phytoplankton in the Dapeng Bay, South China Sea [J],” Acta Oceanol Sin, Vol. 18, No. 1, pp. 103–108, 1999.

[11] J. G. Wu, J. H. Huang, X. G. Han, Z. Q. Xie, *et al*. “Three-Gorge Dam–Experiment in habitat fragmentation [J],” Science, No. 300, pp. 1239–1240, 2003.

[12] L. Ye, D. F. Li, T. Tang, X. D. Qu, *et al*. “Spatial distribution of water quality in Xiangxi River, China [J],” Chin J Appl Ecol, Vol. 14, No. 11, pp. 1959–1962, 2003. [in Chinese]

[13] T. Tang, D. F. Li, W. B. Pan, *et al*. “River continuum characteristics of Xiangxi River [J],” Chin J Appl Ecol, Vol. 15, No. 1, pp. 141–144, 2004. [in Chinese]

[14] H. Y. Wang, “Effects of the Three Gorges Reservoir on the water environment of the Xiangxi River with the proposal of countermeasures [J],” Resour Environ Yangtze Basin, Vol.14, No. 2, pp. 233–237, 2005. [in Chinese]

[15] X. C. Jin and Q. Y. Tu, “Criterion of eutrophiction survey on lakes [M],” 2nd ed, Beijing: Environmental Sci Press, 1990. [in Chinese]

[16] A. J. Lewitus, E. T. Koepfler, and J T. Morris, “Seasonal variation in the regulation of phytoplankton by nitrogen and grazing in a salt marsh estuary [J],” Limnol Oceanogr, No. 43, pp. 636–646, 1998.

[17] G. Pedersen, K. S. Tamde, and E. M. Nilssen, “Temporal and regional variation in the copepod community in the Central Barents Sea during spring and early summer [J],” J Plankton Res, Vol. 7, No. 2, pp. 263–282, 1995.

[18] S. S. S. Lau and S. N. Lane, “Biological and chemical factors influencing shallow lake eutrophication: A long–term study [J],” Sci Total Environ, Vol. 288, No. 3, pp. 167–181, 2002.

[19] L. Fu, “Grey systematic theory and its application [M],” Beijing: Science and Technology Documentation Publishing House, 1992. [in Chinese]

[20] X. Y. Shao, Y. Y. Xu, X. Q. Han, *et al*. “The distribution of chlorophyll a content and primary productivity in Guangzhuangping Bay of Xiangxi River [J],” Acta Hydrobiologica Sinica, Vol. 30, No. 1, pp. 95–100, 2006. [in Chinese]

[21] J. L. Stoddard, “Long-term changes in watershed retention of nitrogen: its causes and aquatic consequences. In: L A Baker (ed.), Environmental Chemistry of Lakes and Reservoirs, Advances in Chemistry [M],” Series 237, pp. 223–284, Washington DC, 1994.

[22] Z. S. Liu, C. S. Wang, J. Y. Ni, G. H. Zhu, *et al*. “Ecological distribution characteristics of chlorophyll a in Fuxian Lake [J],” Acta Ecologica Sinica, Vol. 23, No. 9, pp. 1773–1780, 2003. [in Chinese]

[23] K. Kotut, S. G. Njuguna, F. M. Muthuri, *et al*. “The physico–chemical conditions of Turkwel Gorge Reservoir, a new man made lake in Northern Kenya [J],” Limnologica, No. 29, pp. 377–392, 1999.

[24] Q. J. Kuang, Y. H. Bi, and G. J. Zhou, “Study on the phytoplankton in the Three Gorges Reservoir before and after sluice and the protection of water quality [J],” Acta Hydrobiologica Sinica, Vol. 29, No. 4, pp. 353–358, 2005. [in Chinese]

[25] L. Kautsky, “Primary production and uptake kinetics of ammonium and phosphate by Enteromapha Conpressa in an ammonium sulphate industry outlet area [J],” Aquatic Botany, Vol. 12, No. 1, pp. 23–40, 1981.

J. Water Resource and Protection, 2009, 3, 195-202
doi:10.4236/jwarp.2009.13024 Published Online September 2009 (http://www.SciRP.org/journal/jwarp/).

Preparation and Application of Polymer Silicate Phosphate Ferric Sulfate Used in High-Viscosity Oil Refining Wastewater Treatment

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Abstract

A new kind of flocculants, named Polymer Silicate Phosphate Ferric Sulfate(PSPFS), was synthesized by ferrous sulfate used as the main material and activated silicic acid as additive. In this paper, High-Viscosity Oil Refining wastewater from Liaohe Petrochemical Corporation was the treatment object. Overall, the influencing factors and synthesis technology conditions of PSPFS were determined by experiments. First of all, the conditions of influencing factors were showed as follows: the mass percent concentration of ferrous sulfate 55%,concentration of sodium silicate 15% , the molar ratio of ferrous sulfate and hydrogen peroxide 1.2：1, oxidation temperature 40 degree Celsius, oxidation time 4 hours, polymerization temperature 60 degree Celsius and polymerization time 2 hours. Secondly, the optimal ratios of components were determined by uniform design method. The molar ratio of Fe/Si is 5.0：1, Fe/H2SO4 is 3.2：1, and Fe/P is 18.0：1. At last, the optimal experimental condition was determined as follows: the dosing quantity 200mg/L, pH value 5.5～9, temperature 25～45℃, stirring time 2 min, and standing time 3 min, according to the result of flocculation experiments with PSPFS. Besides, the result of the comparative experiments showed that the efficiency of PSPFS was much better than the reference flocculants.

Keywords: Polymer Silicate Phosphate Ferric Sulfate, Flocculant, Preparation, High-Viscosity Oil Refining Wastewater

1. Introduction

High-Viscosity Oil is abundant in China and has an annual output of more than 30 million ton. It makes an essential role in the petrolic exploration and development. In the exploitation process, High-Viscosity Oil will generate a large number of mining liquid which is consisted of crude oil, silt and water. The ratio of oil/ water is highly changeable, since it depends on many factors, such as oil reservoir geology, the service life of oil wells, and the relationship between steam and oil wells and so on. In most cases, the volume of water in mining liquid is twice to 20 times than that of oil, for about four times usually [1]. The High-Viscosity Oil Refining composition is extremely complex. And how to disposal such kind of wastewater becomes the important factor which restricts the development of High-Viscosity Oil Refining. Therefore, researches on the treatment of High-Viscosity Oil Refining wastewater have essential theoretical and practical significance. There are many kinds of methods to treat High-Viscosity Oil Refining wastewater, such as physical methods, physical-chemistry methods, biochemistry methods [2–4] and so on. Flocculation is a major method. Especially, silicon polymers have caused widespread concern [5–7], due to the new flocculants with high-strength polymer capacity in the physical and chemical processing.

2. Experimental Medicaments and Materials

2.1. Experimental Medicaments

The major experimental medicaments include: $FeSO_4 \cdot 7H_2O$, $Na_2SiO_3 \cdot 9H_2O$, H_2SO_4, H_2O_2, phosphating

Table 1.The water quality index of water sample. mg/L

Oil	sulfur	hydroxybenzene	COD
1305	21.34	59.24	2865

stabilizer, petroleum ether, anhydrous sodium sulfate, NaOH and so on.

2.2. Equipments

The major equipments include: 752 spectrophotometer, magnetic heating stirrer, pHS-2 acidometer, electronic analytical balance, vacuum pump, glass funnel, vacuum filter bottles, colorimetric tube, volumetric flask, burette, and so on.

2.3. Test Water Samples

The test water samples from wastewater treatment plant of the Liaohe Petrochemical Company. They were mainly originated from the crude oil dehydration, various refineries, coking plant and petrochemical installations drainage and a small amount of sewage. Water quality (pH=8.24) is shown in Table. 1.

2.4. Testing Methods

The oil content in samples was tested by the 752 spectrophotometer.

3. The Preparation of Polymer Silicate Phosphate Ferric Sulfate

3.1. The Preparation Principle

In acid conditions, $FeSO_4$ was oxidized to $Fe_2(SO_4)_3$, then hydrolysis, polymerization reaction of red-brown polyferric sulfate. The main reaction is as follows:
Oxidation:

$$2FeSO_4 + H_2O_2 + H_2SO_4 \rightarrow Fe_2(SO_4)_3 + H_2O \quad \textbf{(1)}$$

Hydrolysis:

$$Fe_2(SO_4)_3 + nH_2O \rightarrow Fe_2(OH)_n(SO_4)_{3-\frac{n}{2}} + \frac{n}{2}H_2SO_4 \quad \textbf{(2)}$$

Polymerization:

$$m\left[Fe_2(OH)_n(SO_4)_{3-\frac{n}{2}}\right] \rightarrow \left[Fe_2(OH)_n(SO_4)_{3-\frac{n}{2}}\right]_m \quad \textbf{(3)}$$

In the polymerization process, activated phosphate and silicate are added step-by-step, and copolymerized with the polyferric sulfate. In this way, we can get the PSPFS. The essence is that coordinated water molecules in hydrated cation dissociated H^+ step by step in the process of forming covalent complexes by ferric ions. With the H^+ dissociation, it forms a series of hydroxyl complexes. Mononuclear complexes can generate hydroxyl polynuclear complexes in the process of hydroxyl connection. In general, it can be easier to form hydroxyl complexes when the iron concentration is larger. In the effect of high temperatures, long-term aging or (and) pH, the hydroxyl connected complexes can be transformed into oxygen connected complexes. There are two ways to form these complexes. One is that the irreversible M-O-M bonds are formed by eliminating monomolecular water between two adjacent hydroxyl bridges. The other is formed by dehydrogenation from hydroxyl. Sillen has presented the "root + section" hypothesis in order to illustrate the formation mechanism of multi-core hydroxyl connection complexes. He said that the $M(OH)_t^{(n-t)+}$ is added to the cation or cation groups gradually as chain section in the hydrolysis as shown in Figure 1.

3.2. The Synthesis of Polymer Silicate Phosphate Ferric Sulfate

We added some concentrated sulfuric acid in a certain quantity concentration of $FeSO_4{\cdot}7H_2O$ solution, and got Solution 1. Then we dissolved different quantities of $Na_2SiO_3{\cdot}9H_2O$ in 100ml water, added appropriate quantity of concentrated sulfuric acid and got Solution 2 after activation. At last, we mixed the two solutions, and added phosphate stabilizing agent and 30% H_2O_2 in order to oxidize Fe^{2+} into Fe^{3+}. We got the solid product, after baking the product, reddish-brown viscous liquid, which was generated from polymerizing reaction in certain temperature.

The process is shown in the Figure 2.

3.3. Determination of the Synthesis Conditions of Polymer Silicate Phosphate Ferric Sulfate

3.3.1. The Concentration of $FeSO_4$

On one hand, the Fe^{2+} and oxidated Fe^{3+} increase as the increasing of the concentration of $FeSO_4$, which has promoted the polymerization reaction. On the other hand, the product stability and effective components will decline, because the generation probability will increase, which of hydroxyl complexes to precipitate alkaline $Fe_2(SO_4)_3$ in the hydrolysis process. In order to reduce sedimentation, it needs to increase the acidity of the solution. But it will lead to the descent of product basicity and go against to improve the products' overall quality. Consequently, it doesn't mean that the higher iron content, the better the effect of synthesis. If the iron concentration reaches the designed target, the major measure to improve product quality is to enhance its basicity. Considered literatures and feasibility of tests, the concentration of $FeSO_4{\cdot}7H_2O$ is 55% (mass percentage) in this experiment.

3.3.2. The Dosage of H_2O_2 and the Temperature

We used H_2O_2 as the oxidant in our experiment. The dosage of H_2O_2 not only determines whether Fe^{2+} can be

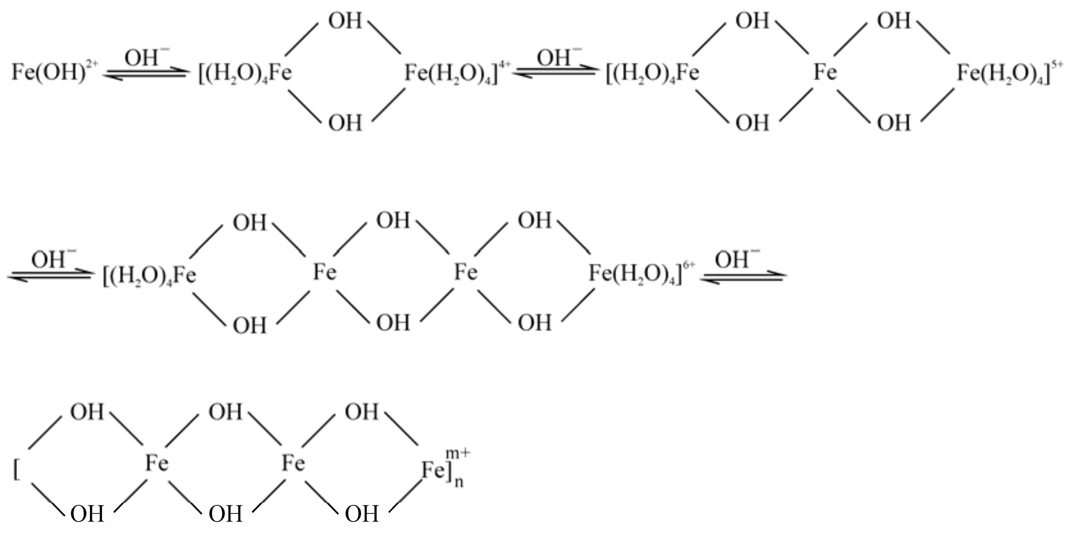

Figure 1. Hydrolytic-polymeric process of Fe^{3+}.

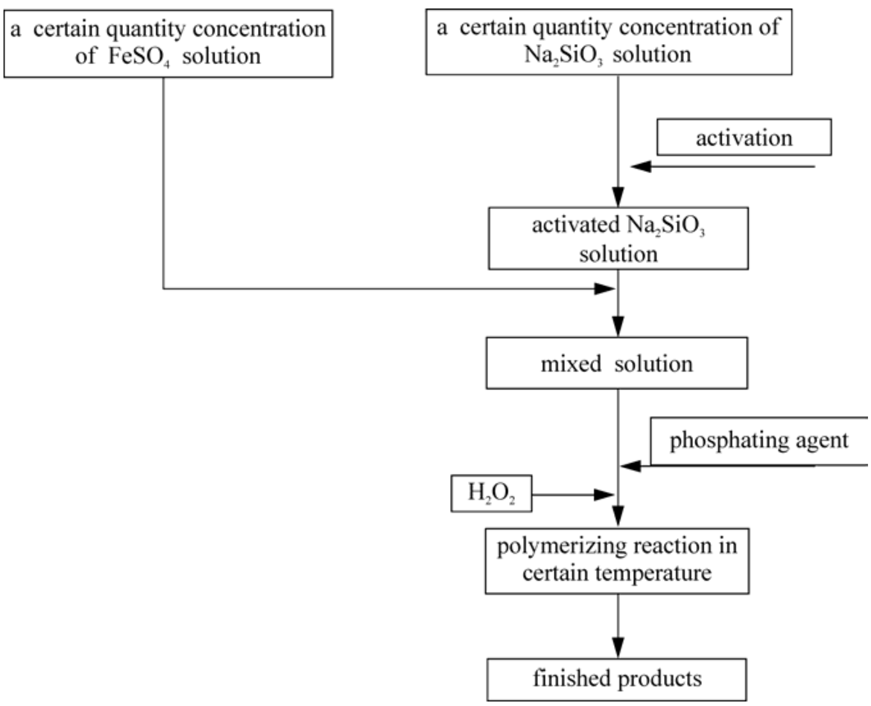

Figure 2. Preparation technology of polymeric phosphate ferric sulfate silicate.

transformed into Fe^{3+} completely, but also infects the quality of the final products. If the dosage of H_2O_2 is not enough, the quality of the final products will reduce as the effective components decline. It shows that, Fe^{2+} can not be detected when molar ratio of H_2O_2/Fe^{2+} was 1.2:1 in our experiment. As a result, it is determined that its ratio is 1.2:1.

It is exothermic reaction when Fe^{2+} transformed into Fe^{3+}, therefore, it increases the temperature of the reaction system, and accelerates the decomposition of hydrogen peroxide. We used normal temperature water-bath to control the temperature in the experiment.

3.3.3. The Concentration of Sodium Silicate Solution and the Dosage of Activated Acid

According to the experiments, we found that it could cause the experimental failure when the concentration of sodium silicate was more than 20.0%. In the activation process, a few light blue floccules appeared, and formed gel immediately. Therefore, it must be controlled that the concentration of sodium silicate is below 15% in the experimental process. Also, the dosage of activated acid influenced the polymerization of Polymer Silicate Phosphate Ferric Sulfate in the activation process. The experiment shows that we can get the uniform and stable activated silicic acid, if the concentration of H_2SO_4 was adjusted to 2%. Therefore, it is determined that the concentration of H_2SO_4 is 2% in our study.

3.3.4. Temperature and Time of Polymerization

Both temperature and time are important factors which influence the product quality, and directly determine the production cycle and applied efficiency of products. If polymerization temperature was too high, and polymerization time was too long, it would enhance water evaporation intensively, decline product stability, generate turbidity and precipitated, and cause long production period. In contrary, if the temperature was low, and time was short, it would lead to incomplete polymerization and inefficient purification effect. According to the experiment, the optimal temperature of polymerization is 60℃, while the optimal time of that is 2 hours.

3.4. The Optimal Ratio of Components in the Synthesis Process of Polymer Silicate Phosphate Ferric Sulfate

According to the analysis above, it is clear to see that the ratio of ferric ion and sulfuric acid, ferric ion and silicate, and ferric ion and phosphate radical are determining factors of PSPFS's synthesis and product quality. In the synthesis process, pH value can be controlled by the dosage quantity of the concentrated sulfuric acid. And the ratio of ferric ion and silicate, and that of ferric ion and phosphate radical can be controlled by the dosage quantity of phosphoric acid and sodium silicate in reaction. The three factors have mutual restriction and affect the ultimate effect separately; therefore, the effects of the other two factors should be considered when one of the factors is regulated. We performed the uniform design experiment to confirm the optimal ratio of components of PSPFS which could be suitable for High-Viscosity Oil Refining wastewater treatment. The schedule of experimental elements is shown in Table. 2.

In order to research the flocculation effect of PSPFS which was synthesized in different conditions, we used flocculation methods to treat High-Viscosity Oil Refining Wastewater. And the dosing quantity of $FeSO_4$ was 200mg/L.The results and phenomena are shown in the Table 3.

On the basis of multiple regression analysis of experimental results [8], we determined the optimal ratio of components in the synthesis process of PSPFS as is shown in the Table4 after considering product stability, treatment efficiency and so on.

4. The Application of PSPFS in the Flocculation Treatment of High-Viscosity Oil Refining Wastewater

4.1. Determination of the Optimal Experimental Conditions

In order to optimize the experimental conditions, we performed the experiments to treat real wastewater from High-Viscosity Oil Refining Corporation.

Table 2. Schedule of experimental element.

Experimental serial number	Mol ratio of ferric ion and silicate（X1）	Mol ratio of ferric ion and sulfuric acid（X2）	Mol ratio of ferric ion and phosphate（X3）
1	4.46	1.95	5.70
2	2.90	1.21	3.25
3	2.26	1.49	8.59
4	11.23	2.17	4.32
5	5.21	1.41	13.24
6	3.57	2.17	5.66
7	2.81	2.33	21.97
8	10.37	1.58	7.35
9	5.73	4.62	44.26
10	4.10	2.44	9.59

Table 3. The experimental result and phenomenon of each level.

The level of the serial number	Average absorbance A	Oil content（mg/L）	Experimental phenomena
1	0.429	59	Synthetic products were steady; sedimentation was not apparent within 10 days; there were sank floccules after the treatment.
2	0.744	105	There were a small amount of floccules in oxidation process. After oxidation, the floccules disappeared. The stability of synthetic products was poor and a few precipitates appeared after 24 hours. There were sunk floccules after the treatment.
3	0.503	70	Synthetic products were steady; sedimentation was not apparent within 10 days; there were sank floccules after the treatment.
4	0.377	52	Synthetic products were steady; sedimentation was not apparent within 10 days; there were sank floccules after the treatment.
5	0.343	47	The stability of synthetic products was poor; gel phenomenon appeared after 24 hours; there were sunk floccules after the treatment.
6	0.433	60	The stability of synthetic products was poor; gel phenomenon appeared after 24 hours; there were sank floccules after the treatment.
7	0.381	52	Synthetic products were steady; sedimentation was not apparent within 10 days; there were floated floccules after the treatment.
8	0.345	47	Synthetic products were unsteady; partial gel appeared after 24 hours; there were sank floccules after the treatment.
9	0.367	50	Synthetic products were unsteady; a small amount of $Fe(OH)_3$ precipitated; there were sunk floccules after the treatment.
10	0.247	33	Synthetic products were steady; sedimentation was not apparent within 10 days; there were sank floccules after the treatment.

Table 4. The optimal ingredient of composition.

Mol ratio of ferric ion to silicate	Mol ratio of ferric ion to sulfuric acid	Mol ratio of ferric ion to phosphate
5.0	3.2	18.0

4.1.1. Determination of Flocculant Dosage

The dosage not only impacts the oil removal efficiency, but also the cost of medicament. The result of different dosage is shown in Figure 3.

As shown in Figure 3, the optimal dosage is in the range of 200～250mg/L. Given the economic efficiency, 200mg/L is the most suitable.

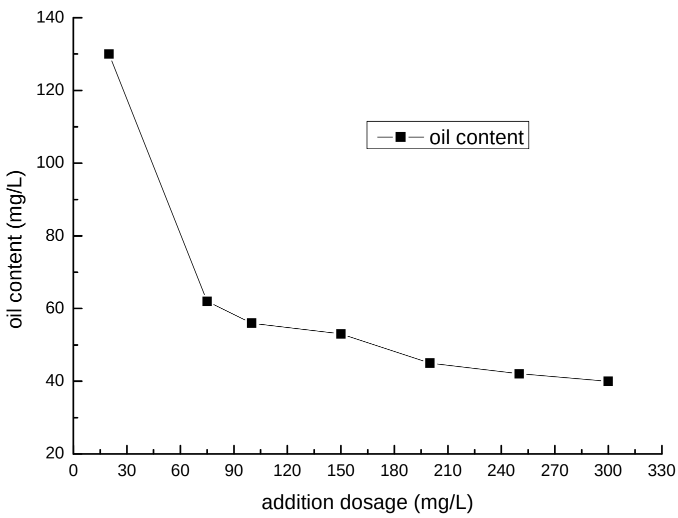

Figure 3. Effect of flocculant addition on removal efficiency of oil.

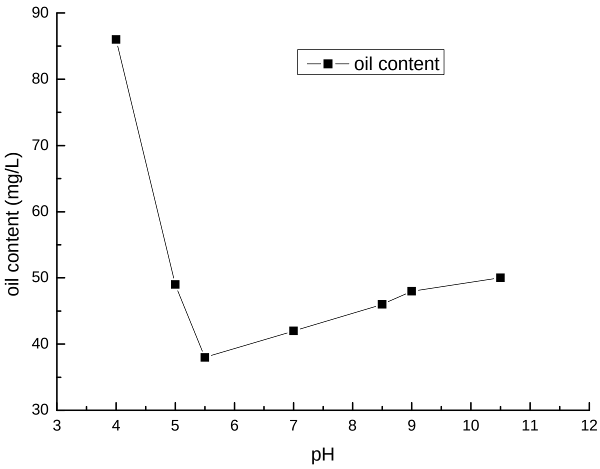

Figure 4. Effect of pH on removal efficiency of oil.

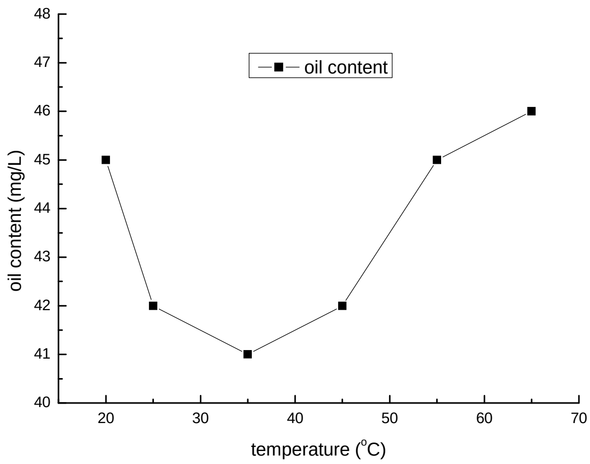

Figure 5. Effect of temperature on removal efficiency of oil.

4.1.2. The Determination of pH

In order to research the effect of pH value on the flocculation experiment, we added PSPFS with dosage quantity of 200mg/L in the High-Viscosity Oil Refining Wastewater with different pH value. The result is shown in Figure 4.

From Figure 4, the optimal pH value is in the range of 5.5～9. It is clear to see that the removal efficiency was low if the wastewater was strong acid or weakly-alkaline. There are two reasons. One is that a great deal of H^+ generated in the wastewater, and prevented the polynuclear hydroxo iron from generating in strong acid condition. The other reason is that a mass of OH^- changed polynuclear hydroxo iron into $Fe(OH)_3$ which precipitated from the water in alkaline condition. However, the effect in alkaline was small than that in strong acid. It is due to that the silicon and phosphor in PSPFS displayed buffer action. After investigating the monitoring data in Liaohe Petrochemical Corporation, we found that the pH value of wastewater was in the range of 5～10, and its average value was 8.0. Therefore, it has on need to regulate pH value in practical operation.

4.1.3. The Determination of Temperature

Temperature is another condition that will impact the flocculation efficiency. As a result, we preformed a set of experiment with different temperatures of samples. In the experiment, the dosage was 200mg/L, and pH value was 5.5. The result is shown in Figure 5.

It is shown in Figure 5 that the optimal temperature is between 25～45°C. It will reduce the effect of flocculation if the temperature is too high or too low. Virtually, if the temperature is low, not only the speed of Brownian motion will decline, but also the collision probability between flocculants and oil molecules will decrease. In contrary, high temperature will accelerate the reaction rate, generate small flocs, enhance the hydration of the small flocs, and slow down their settling velocity. Overall, excessive water temperature is adverse to flocculation. In practical operation, we needn't regulate the temperature of the sewage of Liaohe Petrochemical Company, which is in the optimal temperature range.

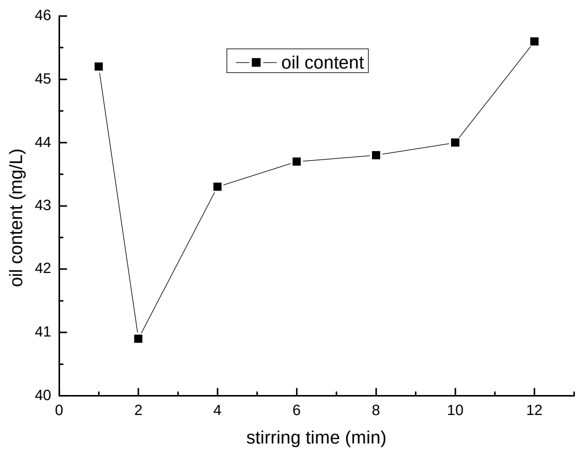

Figure 6. Effect of stirring time on removal efficiency of oil.

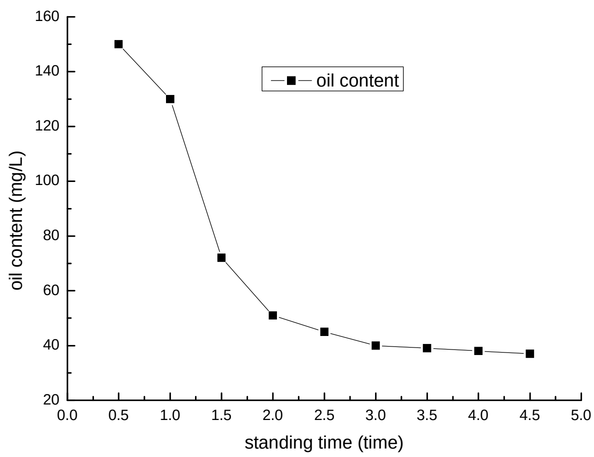

Figure 7. Effect of standing time on removal efficiency of oil.

4.1.4. The Determination of Stirringing Time

We performed the experiment with different stirring time of wastewater. The result is shown in Figure 6.

As it is shown in Figure 6, when the stirring time is 2 minutes, the removal efficiency of oil is highest of all. If the time is too long or too short, the removal efficiency is low. One of the main reasons is that the flocculants and wastewater aren’t mixed intensively, and the hydrolysis is not complete in short stirring time. The other reason is that stirring for a long time will destruct the flocs, make saturation absorption flocs desorpt easily, and be dis-benefit to the conglomeration and accretion of small flocs. Overall, according to the effect of stirring time on the removal efficiency, the optimal stirring time is two minutes.

4.1.5. The Determination of Standing Time

We determined oil content of the supernatant liquid after different standing time. The result is shown in Figure 7.

In Figure 7, it is shown that the optimal standing time is 3 min. When the standing time is less than 2 min, the flocculation do not finish and the flocs suspend in the liquor. In this situation, the oil content is high. In contrary, when the standing time is over 3 min, the flocs generate in the liquor almost precipitated and flocculation are finished. In this situation, the oil content drops to about 30mg/L. As the increase of the standing time, the oil content drops continually, but inconspicuously. Overall, according to the economic benefits and practical requirements, the optimal standing time is 3 min.

4.2. The Comparison of PSPFS and Reference Flocculants Used in Practical Operation

In order to investigate more about the flocculation effect of PSPFS, we performed a great number of repeated experiments in the optimal condition of PSPFS’s flocculation. We compared the removal efficiencies of oil, COD, sulfur and phenol between PSPFS and reference flocculants in the wastewater treatment plant of Liaohe Petrochemical Corporation. The results are shown in Figure 8–11 separately.

In Figure 8–11, it is clear to see that the removal efficiency of PSPFS is much better than the reference flocculants used in wastewater plant. In Table.5, it shows the average efficiencies of the two flocculants to removal the four pollutants.

5. Conclusion

1) This paper analyzed the effect of PSPFS’s synthesis factors on output quality. According to our experiment, it is determined as follows: mass percent concentration of ferrous sulfate 55%, concentration of sodium silicate 15%, mol ratio of ferrous sulfate and hydrogen peroxide 1.2:1, oxidation temperature 40 degree Celsius, oxidation time 4 hours, polymerization temperature 60 degree Celsius, and polymerization time 2 hours.

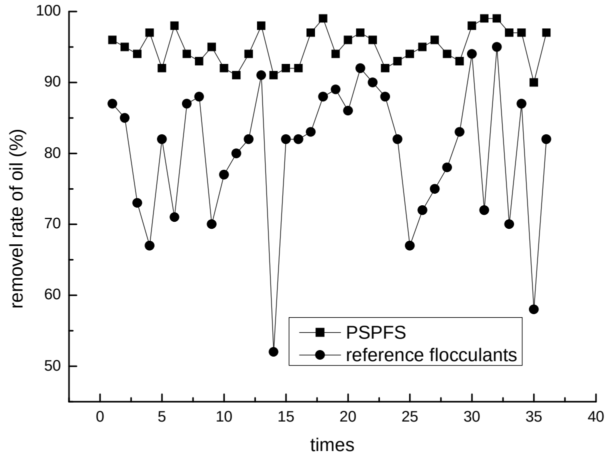

Figure 8. The comparison of oil removal efficiency.

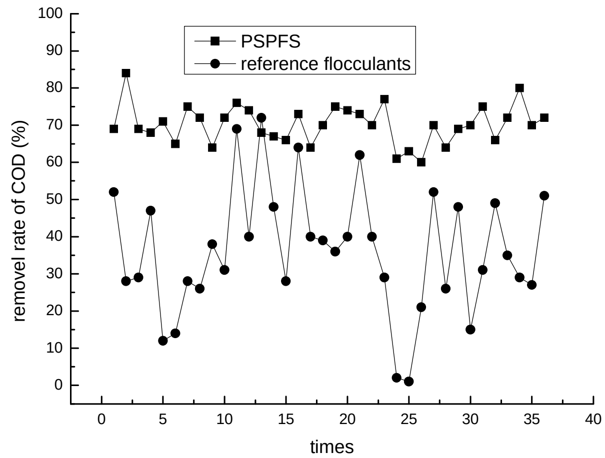

Figure 9. The comparison of COD removal efficiency.

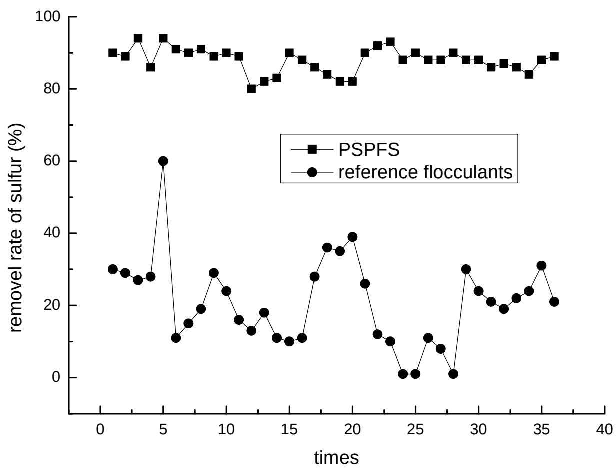

Figure 10. The comparison of sulfur ion removal efficiency.

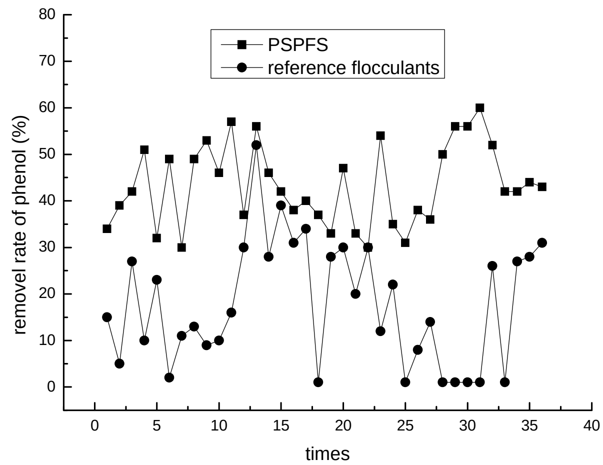

Figure 11. The comparison of phenol removal efficiency.

2) According to equal designed experiment, we obtained the oil removal efficiencies of PSPFS which was synthesized in different conditions. Considered comprehensively the factors, such as stability, removal efficiency and so on, the optimal ratios of components of PSPFS were determined as follows: molar ratio of Fe/Si 5.0:1, Fe/H_2SO_4 3.2:1, and Fe/P 18.0:1.

3) The PSPFS was used to treat actual High-Viscosity Oil Refining wastewater of Liaohe Petrochemical Corporation. The result shows that its optimal dosage quantity is 200mg/l, pH value is between 5.5 and 9, temperature is between 25 and 45^{o}C, stirring time is 2 min and standing time is 3 min.

4) A set of contrast experiments was performed to compare PSPFS and flocculants used in wastewater treatment of Liaohe Petrochemical Corporation. The result shows that the treatment efficiency of PSPFS is higher than those of the reference flocculants. The average removal efficiency of oil was 94.1%, COD was 69.4 %, sulfide was 88.9% and volatile phenol was 43.5%, when PSPFS was used to treat the wastewater. And the average removal efficiency of oil was 80.5%, COD was 35.8%, sulfide was 21.1 %, and volatile phenol was 17.3%, when reference flocculants was used. In addition, the treatment efficiency of PSPFS was more stabile than that of the reference flocculants.

6. References

[1] R. Zhang, “The technology of heavy oil thermal recovery,” Beijing: Petroleum industry press, 1999.

[2] H. Y. Hao, ZW Cui, and H. Y. Hao, “Studies and applications of flocculants in water treatment,” Journal of North China Institute of Technology, No. 2, pp. 137–140, 1999.

[3] X. Y. Xu and N. N Gu, “Screening and domestication of microorganism used in oil contaminated wastewater remediation [J],” Journal of Northeastern University: Natural Science, No. 5, pp. 721–724, 2007.

[4] X. Y. Xu and N. N. Gu, “Chemical embedding immobilization technique of microorganism used in oil contaminated wastewater remediation,” Transaction of NEU, No. 9, pp. 1329–1332, 2007.

[5] B. Y. Gao, H. H. Hahn, and E. Hoffmann. “Evaluation of aluminum-silicate polymer composite as a coagulant for water treatment,” Water Research, Vol. 36, No. 14, pp. 3573–3581, 2002.

[6] A. K. Arnold-Smith and R. M. Christie, “Polyaluminum silicate sulfate-A New coagulant for potable and wastewater treatment,” Proc of the 5th Gothenburg Symposium, France, 1992.

[7] B. Y. Gao, Q. Y. Yue, and B. J. Wang, “Poly-aluminum–silicate-chloride (PASiC)-A new type of composite inorganic polymer coagulant,” Colloids and Surfaces A: PHysicochemical and Engineering Aspects, Vol. 229, No. 1–3, pp. 121–127, 2003.

[8] L. J. Li, “Preparation of polymer silicate phosphate ferrous sulfate and its applicant on high-viscosity oil refining wastewater treatment [D],” Northeastern University, 2004.

J. Water Resource and Protection, 2009, 3, 203-209
doi:10.4236/jwarp.2009.13025 Published Online September 2009 (http://www.SciRP.org/journal/jwarp/).

Pilot Study of Ultrafiltration-Nanofiltration Process for the Treatment of Raw Water from Huangpu River in China

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Abstract

Pilot-scale test was carried out to evaluate the performance of a combined ultrafiltration (UF)-nanofiltration (NF) membrane process for the treatment of raw water from Huangpu River, Shanghai, in China. Results showed that UF could significantly remove turbidity, iron and manganese, and also could retain a part of high molecular weight (MW) organic compounds. Subsequently, NF could further reject low MW organics and inorganic salts, and ensured the treated water to reach the Standards for Drinking Water Quality in China. It seemed that 90 L/m^2·h was an appropriate permeate flux for UF system when the raw water was directly filtered by UF membrane, the addition of coagulant (alum or ferric chloride) was not preferable to mitigate the fouling of the UF membrane. After near 120 days operation, the permeate flux of NF could be maintained at 24-25 L/m^2·h steadily, and no chemical clean was required.

Keywords: Ultrafiltration, Nanofiltration, Permeate Flux, Fouling

1. Introduction

As the main drinking water source of Shanghai, the largest city in China, the Huangpu River provides 4x10^6 m^3 raw water every day to the city (accounting for 70% of its total daily water demand). Due to the increasing industrial pollution, the raw water quality of Huangpu River has been deteriorated in recent years. However, most of local water plants are employing conventional surface water treatment processes, which consist of coagulation, flocculation, sedimentation, rapid sand filtration and disinfection. These processes focus primarily on the removal of turbidity, colloid and pathogens, but are typically ineffective in reduction of dissolved organic pollutants, which may produce adverse impacts to human health (e.g. formation of disinfection byproducts during chlorination). Consequently, the finished water produced by these plants is difficult to completely comply with the Standards for Drinking Water Quality of China(GB5749-2006). To provide safe and clean drinking water, reliable and effective alternatives for conventional treatment processes are highly required.

Membrane processes, which are considered as innovative water treatment technologies, are gaining more and more attention due to their advantages compared with conventional processes, such as low chemical dosage, high separating efficiency, particularly in their effectiveness in the control of micropollutants in drinking water [1–3]. In this study, a combined UF-NF process was used to evaluate the performance on the treatment of raw water from Huangpu River.

2. Materials and Methods

2.1. Experimental Set- up

The pilot scale set-up was installed in the intake pump station of the Minhang Second Waterplant, Shanghai, China, with a designed flow rate at 3-5 m^3/h (shown in Figure 1).

A laminated filter was installed before the UF booster pump to remove the particles with the diameter larger than 150 μm. The UF membrane(LH3, Lisheng Company, China), in-pressure hollow-fiber type, was made of PVC alloy, the effective filtration area of the membrane was 40m^2, and the molecular weight cut-off (MWCO) was 100,000 Dalton(Da). The UF system operated at a

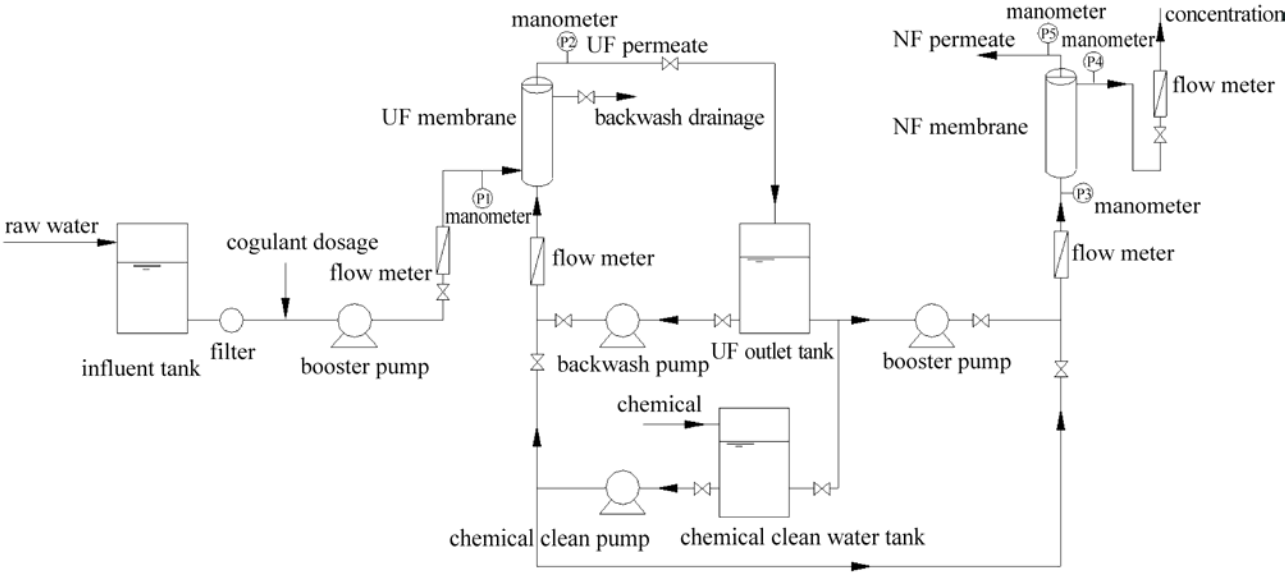

Figure 1. Schematic diagram of experiment set-up.

Table 1. Raw water quality statistics of Huangpu River(Songpu Bridge-Minhang section, 2003–2005).

quality parameters	2003		2004		2005	
	range	average	range	average	range	average
Temperature/℃	2.5~32.5	17.7	3.5~31.5	18.8	4.5~30.0	19.5
Turbidity/NTU	15~113	44	19~150	52	18~135	44
pH	6.9~7.8	7.40	7.0~7.9	7.44	7.0~7.9	7.49
Ammonia/mg/L	0.05~1.70	0.65	0.05~3.00	1.13	0.06~3.30	1.03
Nitrite/mg/L	0.01~0.33	0.102	0.016~0.5	0.136	0.01~0.39	0.143
COD_{Mn}/mg/L	4.40~6.80	5.68	4.50~7.30	5.98	4.90~8.30	6.05
Dissolve oxygen（mg/L）	0.6~10.6	4.8	0.4~9.6	4.74	0.8~11.5	4.76
iron/mg/L	0.25~2.40	1.08	0.27~5.00	1.70	0.75~5.50	1.95
manganese/mg/L	0.07~0.39	0.16	0.050.43	0.18	0.050.72	0.19

dead-end filtration mode, and the backwash cycle was set at 30 minute. Once the operating pressure of the UF membrane ($\Delta P=P_1-P_2$) went up to near 0.1 MPa, a chemical clean would be executed to restore the membrane flux.

NF system was composed of 10 set of NF90-4040 (Dow Company), the total effective filtration area was $76m^2$, the membrane was made of aromatic polyamide and polypiperazine, and the MWCO of NF was 200-300 Da. The NF system operated at a cross-flow mode, and the recovery rate was set at 50%.

2.2. Quality of Raw Water

The raw water quality of Huangpu River (Songpu Bridge-Minhang section, 2003~2005) was shown in Table 1, the main pollutants in the raw water were ammonia, COD_{Mn}, iron and manganese, which all exceed the standard required by Environmental Quality Standards for Surface Water (GB3838-2002,China)

2.3. Analytical Methods

The operating pressure of the membranes was calculated every hour by the record from the manometers. The influent and effluent of UF and NF were collected once every 2 or 3 days, all samples were stored in the refrigerator at 4°C and were analyzed within 24h. Turbidity was measured by a turbidity meter (2100N, HACH). UV_{254} was measured by a spectrophotometer (UV Spectrumlab 52, Lingguang Co.) after the samples were filtered by 0.45μm membranes. The molecular weight (MW) distribution of organics was determined using the UF fractionation method [4]. TOC was measured by TOC analyzer (TOC-5000A, Shimadzu). Assimilable organic carbon (AOC) measurement was carried out using a method modified by Liu etal. [5], which was developed based on the procedures of Van der Kooij et al. [6]. And the other parameters were tested according to GB/T5750- 2006 (China).

3. Results and Discussion

3.1. Removal of Turbidity by UF–NF System

The removal of turbidity by UF-NF system was shown in Figure 2, Although the turbidity of raw water varied broadly within 19-83 NTU, UF could achieve a rejection of 99% and assure 0.1-0.2NTU in effluent, NF could further reduce the turbidity to less than 0.1 NTU and increased the overall removal to 99.8%.

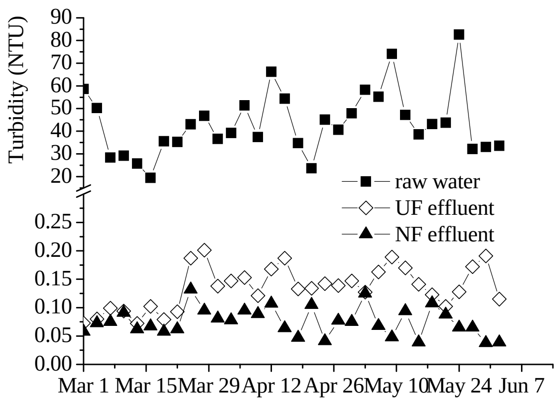

Figure 2. Turbidity removal by UF-NF system.

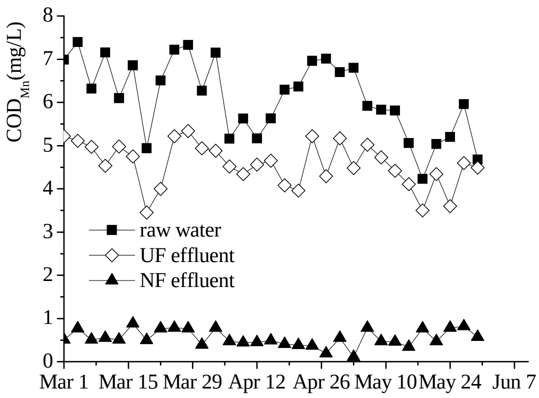

Figure 3. COD_{Mn} removal by UF-NF system.

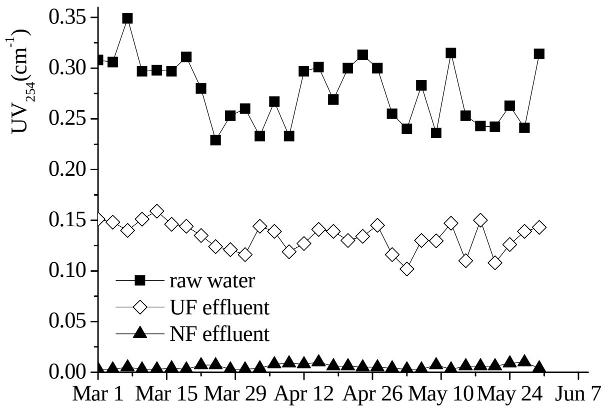

Figure 4. UV_{254} removal by UF-NF system.

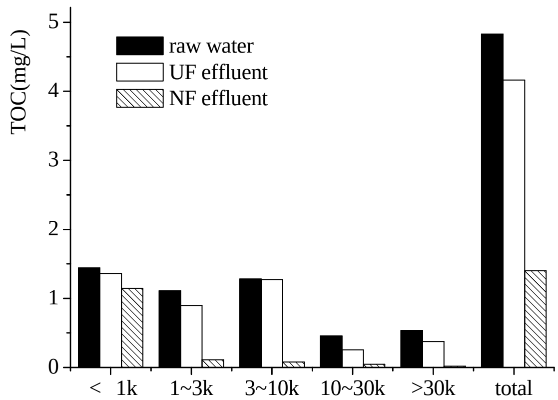

Figure 5. MW Distribution of Organics in Raw Water, UF Effluent and NF Effluent

3.2. COD_{Mn} and UV_{254} Removal by UF–NF System

Figure 3 and 4 showed COD_{Mn} and UV_{254} removal by UF–NF system. COD_{Mn} of the raw water varied within 4.2-7.4 mg/L, and could be reduced to 3.5-5.4 mg/L by UF membrane**,** with a removing efficiency of 4.1%-38.8% (averaged at 25.6%). NF membrane could reduce COD_{Mn} to less than 1 mg/L and increase the removing efficiency to higher than 85%.

UV_{254} is another surrogate measurement for the concentration of organic matters, particularly stands for the complex multiaromatic and multiconjugated humic substances in water. The overall removing efficiencies of UV_{254} achieved by UF and NF were 38.1%-59.8% (averaged at 48.2%) and higher than 95%, respectively.

To better understand the characteristics of the two membranes in rejection of organic matters, the MW distribution of dissolved organic compounds of raw water, UF effluent and NF effluent were analyzed, and the results were shown in Figure 5.

In the raw water, organics with MW>10 kDa, 1-10 kDa and <1 kDa were accounted for 21%, 59% and 30%, respectively. UF mainly removed high MW organics, but showed poor rejection to the low MW organics, and the total TOC rejection of UF was only 14%, which implied that UF alone could not provide satisfactory drinking water. NF could reject most of organics with MW >1kDa and increase the total TOC rejection to 72%, and TOC of NF effluent could be reduced to less than 2mg/L.

3.3. Ammonia Removal by UF–NF System

Ammonia removal by UF–NF system (shown in Figure 6) was similar to the removal of COD_{Mn} and UV_{254}. Ammonia in the raw water are mostly composed of low MW organics (e.g. humic acid and fulvic acid), so it is difficult to be removed by UF, but could be rejected by NF effectively.

3.4. AOC Removal by UF–NF System

AOC is a parameter indicating the bacterial stability of water [5, 7], high AOC always means high possibility of bacterial regrowth in water distribution system. N. Park et al found that AOC could significantly removed by NF membrane [8].

AOC of raw water, UF effluent, and NF effluent were shown in Figure 7. UF and NF could reduce AOC from

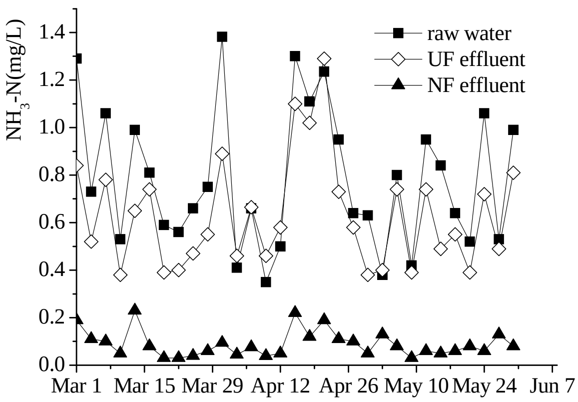

Figure 6. Ammonia removal by UF-NF system.

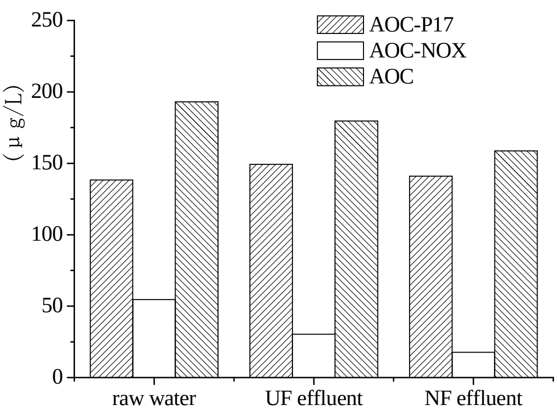

Figure 7. AOC removal by UF-NF system.

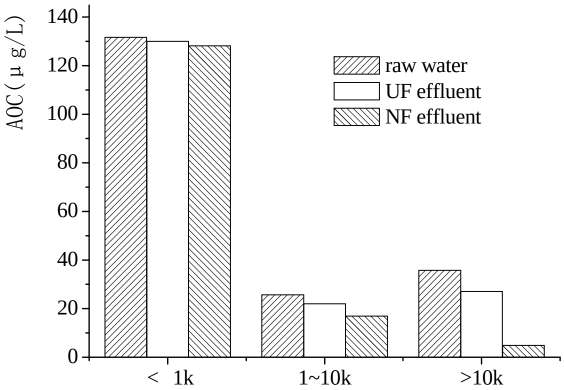

Figure 8. AOC distribution in different MW ranges.

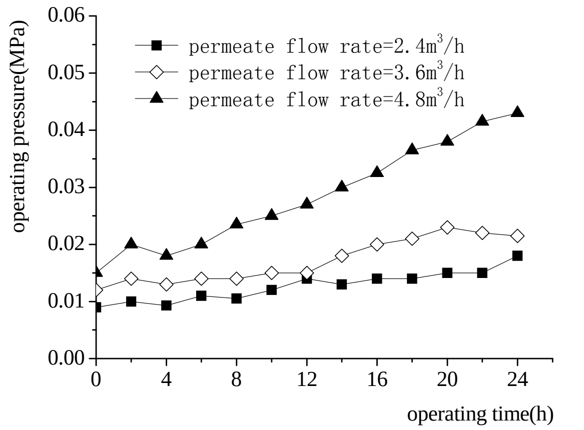

Figure 9. Effect s of permeate flow rate on the UF operating pressure.

193μg/L to 179.7μg/L and 158.7μg/L, respectively, but membranes, especially NF, did not provide adequately high AOC removing efficiency.

The relationship between AOC and MW distribution of organics was also investigated (Figure 8), the result showed that most part of AOC was contributed by low MW organics, which well explained why AOC was so difficult to be removed by membranes.

3.5. Inorganic Salts Removal by UF–NF System

Iron and manganese mainly exist in the water along with colloid [9], so they could be rejected by UF, but to other inorganic salts, the rejection of UF was very poor. Most of inorganic salts were rejected by NF (Table 2), the electrical conductivity of NF effluent could be lowered down to less than 100μs/cm.

3.6. Operation of UF System

The operating pressure increasement of UF at different permeate flow rate was shown in Figure 9. High permeate flow rate always means rapid accumulation of contaminants on the membrane surface and acceleration of

Table 2. Inorganic removal by UF-NF system.

	raw water	UF effluent	NF effluent
Calcium/mg/L	46.3~56.7	45.8~56.2	0.88~1.25
magnesium/mg/L	12.6~15.7	12.4~15.3	0.2~0.6
sodium/mg/L	59.4~67.9	57.6~66.3	5.44~7.06
iron/mg/L	0.27~1.28	0.01~0.12	0.01~0.03
manganese/mg/L	0.13~0.38	0.01~0.1	0.001~0.07
electrical conductivity/μs/cm	601~889	622~750	39~81

the membrane fouling [10]. The result indicated that the operating pressure increased slowly when the permeate flow rate was lower than 3.6 m^3/h., but dramatically went up at 4.8 m^3/h.

C. Guigui, et al found that floc produced during coagulation can form a gel cake layer on the surface of

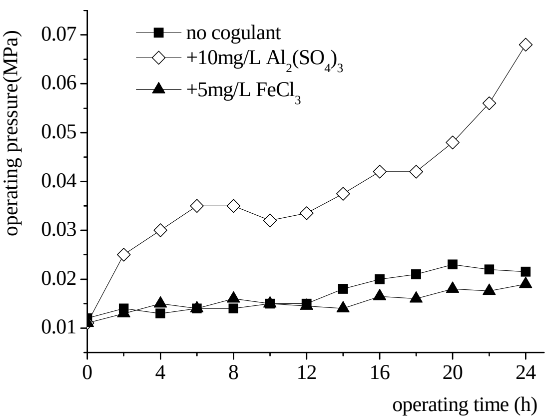

Figure 10. Effects of coagulants addition on the UF operating pressure.

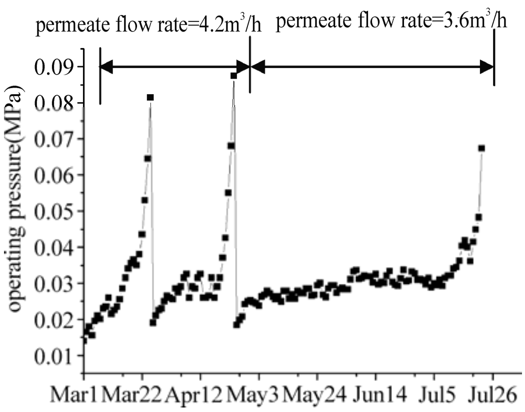

Figure 11. Variety of operating pressure of UF during long time operation.

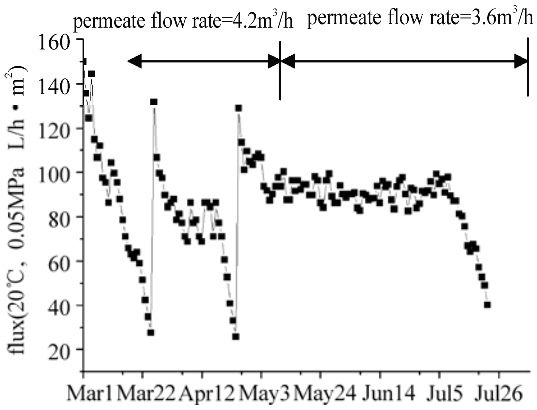

Figure 12. Variety of UF membrane flux during long time operation.

membrane, which may prevent pollutants from contacting with the membrane and slow down the fouling of the membrane [11]. But other researchers found that the dosage of inorganic coagulants may lead to accumulation of salts on membrane surface and accelerate the fouling [12, 13].

The results in Figure 10 showed that the addition of $Al_2(SO_4)_3$ or $FeCl_3$ was not favorable to the operation of UF membrane, especially when the alum was dosed before the membrane. The acceleration of the fouling was mainly caused by the interaction between coagulant and PVC alloy, which was confirmed by the supplier of the membrane.

Figure 11 and Figure 12 showed a long-term performance of the UF system when the raw water was directly filtered by the membrane. The initial pressure loss of the clean membrane was less than 0.02 MPa and gradually increased during the course of filtration. In the first 55 days (from March 6 to April 29), the permeate flow rate of UF membrane was kept at 4.5m^3/h (permeate flux=120L/m^2·h), after 25~30 days, the operating pressure climbed up to 0.08 MPa, and a chemical cleaning was required. But when the flow rate fell to 3.6m^3/h (permeate flux=90L/ m^2·h, from April 6 to July 24), the chemical cleaning cycle could be prolonged to near 90 days. The performance of the UF system was relatively steady at low permeate flux condition.

When the flux of UF membrane was lower than 30 L/ m^2·h in March and April, chemical cleaning was carried out. NaClO was used as cleaning agent in this experiment, after chemical cleaning, more than 90% of the fouling could be eliminated and the flux could be recovered to about 130 L/ m^2·h.

3.7. Operation of NF System

In a 120-day operation (Figure 13), the NF permeate flow rate was maintained at 1.8-2.0m^3/h corresponding to a permeate flux at 24-27 L/ m^2·h. The operating pressure was over 0.7MPa within the first 7 days (in March) when water temperature varied from 13 to 15℃. With the advent of summer, the operating pressure fell to 0.49MPa when the water temperature increased to 25-27 ℃ in July.

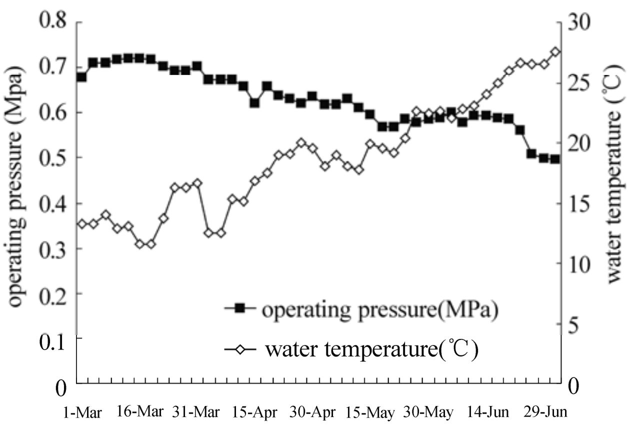

Figure 13. Variety of operating pressure of NF and water temperature during long time operation.

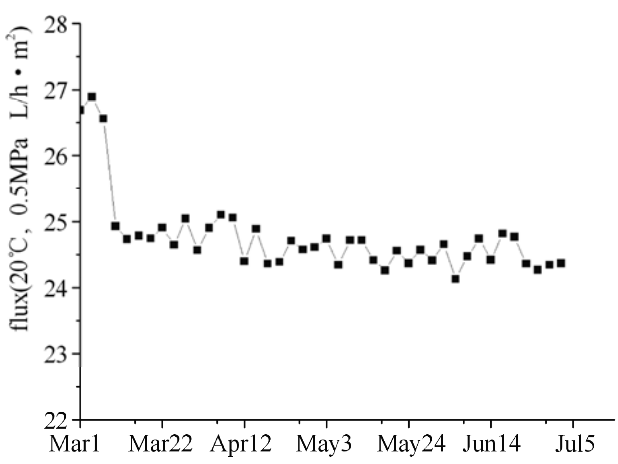

Figure 14. Variety of NF membrane flux during long time operation.

The flux measured at different temperature was corrected to the nominated flux at 25℃ based on the temperature correction coefficients provided by the membrane manufacturer.(shown in Figure 14), the permeate flux dropped drastically from 27 L/ m^2·h to 25 L/ m^2·h in the first 7 days, but after a 120-day continuous operation, the flux was maintained steadily at 24-25 L/ m^2·h, the reduction of NF flux was only 10% and no chemical clean was required.

4. Conclusions

The combined UF-NF process appeared to be a promising technology to remove dissolved organic pollutants from raw water of Huangpu River. UF exhibited an excellent capacity in the respect to reduction of turbidity, iron, manganese, and high MW organics, while NF could further retain relatively low MW organic compounds and inorganic salts. Nevertheless, the UF-NF process showed poor rejection of AOC which was mainly contributed by low MW organic. When the raw water was directly filtered by UF, the UF membrane could operate steadily at a permeate flux of 90 L/h•m^2, the addition of coagulant (alum or ferric chloride) was ineffective in alleviating the fouling of UF membrane**.** In a 120-day continuous operation, no serious fouling was observed in NF membrane, the flux was maintained steadily at 24-25 L/ m^2·h.

5. Acknowledgment

This research was supported by Shanghai Municipal Engineering Design General Institute and Shanghai Minhang Water supply Co. Ltd.

6. References

[1] Y. Magara, S. Kunikane, and M. Itoh, “Advanced membrane technology for application to water treatment,” Wat Sci Tech , Vol. 37, pp. 91–99, October 1998.

[2] AWWA Membrane technology research committee, “Committee report: Membrane process,” JAWWA, Vol. 90, pp. 91–105, June 1998.

[3] S. Kunikane, M. lton, and Y. Magara, “Advanced membrane technology of application to water treatment,” Water Supply, Vol. 16, pp. 313–318, January 1998.

[4] Amy, L. Gary, Collins, R. Michael, Kuo, C. James, King, and H. Paul, “Comparing gel permeation chromatography and ultrafiltration for the molecular weight characterization of aquatic organic matter,” J. AWWA, Vol. 79, pp. 43–39, January 1987.

[5] W. Liu, H. Wu, Z. Wang, S. L. Ong, J. Y. Hu and W. J. Ng, “Investigation of assimilable organic carbon (AOC) and bacterial regrowth in drinking water distribution system,” Water Research, Vol. 36, pp. 891–898. February 2002.

[6] D. Van der Kooij, W. A. M. Hijnen, and A. Visser, "Determining the concentration of easily assimilable organic carbon in drinking water," J. AWWA, Vol. 74, pp. 540–545, October 1982.

[7] P. M. Huck, "Measurement of biodegradable organic matter and bacterial growth potential in drinking water," J. AWWA, Vol. 82, pp. 78–86, July 1990.

[8] N. Park, B. Kwon, M. Sun, H. Ahn, C. Kim, C. Kwoak, D. Lee, S. Chae, H. Hyung, and J. Cho, "Application of various membranes to remove NOM typically occurring in Korea with respect to DBP, AOC and transport parameters," Desalination, Vol. 178, pp. 161–169, July 2005.

[9] C. Cabassud, C. Anselme, and J. J. Bersillon, "Ultrafiltration as a non-polluting alternative to traditional clarification in water treatment," Filtration &separation, Vol. 28, pp.194–198, July 1999.

[10] Z. Wang, J. M. Yao, C. Zhou and J. S Chu, "The influence of various operating conditions on the permeation flux during dead-end microfiltration," Desalination, Vol. 212, pp. 209–218, June 2007.

[11] C. Guigui, J. C. Rouch, L. Durand-Bourlier, V. Bonnelye and P. Aptel, "Impact of coagulation conditions on the in-line coagulation/UF process for drinking water production," Desalination, Vol. 147, pp. 95–100, September 2002.

[12] L. T. Veornique, R. W. Mark, J. Y. Bottero *et al*, "Coagulation pretreatment for ultrafiltration of a surface water, JAWWA, Vol. 82, pp. 76–81, December 1990.

[13] K. Khatib, J. Rose, O. Barres, W. Stone, J. Y. Bottero, and C. Anselme, "Physico-chemical study of fouling membrane mechanisms of ultrafiltration membrane on Biwa Lake(Japan)," Jour Membrane Science, Vol. 130, pp. 53 –62, July 1997.

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doi:10.4236/jwarp.2009.13026 Published Online September 2009 (http://www.SciRP.org/journal/jwarp/).

Effect of Packing Materials and Other Parameters on the Air Stripping Process for the Removal of Ammonia from the Wastewater of Natural Gas Fertilizer Factory

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Abstract

Air-stripping method was used to remove ammonia from the wastewater collected from natural gas fertilizer factory. Different materials were used as packing materials for the air stripping system. The effect of pH over 10.5, air-water flow ratio, nature of packing materials, height of materials and initial influent concentration of ammonia on air stripping unit were investigated. An attempt has been made to find out the stripping constant. Stripping constant was found to be .001, 0014, .001 and .0009 for coal, plastic ring, stone chips and wood chips, respectively. Best result was found for plastic ring for its higher surface area. Wood chips did not give good result, because the chips amalgamate with each other and hence reduces the surface area.

Keywords: Ammonia, Air Stripping, Packing Materials, Stripping Constant

1. Introduction

Industrial pollution is an area of growing environmental concern in Bangladesh. In Bangladesh, industry contributes about 26 per cent to GDP [1]. The Natural Gas Fertilizer Factory Ltd. (NGFFL), Fenchuganj, Sylhet is a pride and pioneer enterprise of the Bangladesh Chemical Industries Corporation (BCIC), was established in December, 1961 in the hilly picturesque surroundings of Fenchuganj to meet the urea demand of the country [2]. NGFFL produces urea. The process involves traditional chemical technology and deals with many chemicals. A part of the chemicals disposed as an industrial effluent in Kushiara River, which is responsible for the of river water quality. Among all the pollutants discharged from a fertilizer factory ammonia has the most severe effect on the receiving water body, soil and air. Ammonia is toxic to fish and aquatic organisms, even in very low concentrations. When levels reach 0.06 mg/L, fish can suffer gill damage. When levels reach 0.2 mg/L, sensitive fish like trout and salmon begin to die. As levels near 2.0 mg/L, even ammonia-tolerant fish like carp begin to die. Ammonia levels greater than approximately 0.1 mg/L usually indicate polluted waters [3]. Bangladesh Industrial Effluent Standards [4], for ammonia nitrogen is 100 mg/L. For the year 2005, the ammonia nitrogen was found above the limit [5]. As NGFFL produces excessive amount of ammonia as effluent and discharges it into the river Kushiara, so treatment of wastewater of NGFFL is very important. This research work has been undertaken to assess the effectiveness of air stripping unit (by using different packing materials) to remove ammonia from wastewater of NGFFL.

2. Air Stripping

Air stripping involves the mass transfer of VOCs that are dissolved in water from the water phase to the air phase. A one-dimensional mass transfer equation is used to describe the mass transfer flux of VOCs transferring from the water phase to the air phase. The equilibrium relationship is linear and is defined by Henry's Law [6]. This mass transfer can be accomplished in a packed -column, a low profile, or a diffused-air air stripper [8]. The following methods are available for determining the size of a packed-column air stripper: Commercial software (Iowa State University), Manufacturer's software (Carbon-air

Environmental Systems), Analytical equations [7, 9, 10, 11] and McCabe-Thiele graphical method [11].

Ammonia stripping is a simple desorption process used to lower the ammonia content of a wastewater stream. Some wastewaters contain large amounts of ammonia and/or nitrogen-containing compounds that may readily form ammonia. It is often easier and less expensive to remove nitrogen from wastewater in the form of ammonia than to convert it to nitrate-nitrogen before removing it [12]. Ammonia Stripping seek to maximize the volatile ammonia component [13]. Ammonium ions in wastewater exist in equilibrium with gaseous ammonia as shown in the following equation:

$$NH_4^+ \leftrightarrow NH_3 + H^+ \quad \textbf{(1)}$$

In ammonia stripping, lime or caustic is added to the wastewater until the pH reaches 10.8 to 11.5 standard units, which converts ammonium hydroxide ions to ammonia gas [14].

3. Methodology

For the air-stripping experiments, one stripping tower of polyvinyl Chloride tube (1981.2 mm height X 50.8 mm internal diameter) was constructed (Figure 1). The tower was packed with plastic ring of 12.7 mm dia, wood chips of 19.05 mm, stone chips of 19.05 mm and coal chips of 19.05 mm (Figure 2) to promote the down flow of liquid in a thin, gentle stream. Five hundred to seven hundred ml of wastewater was used for each experiment. The effluent was collected from the bottom of the tower to measure the concentration of ammonia after collecting 100 and 300 ml of treated wastewater each time. Average was taken as the final concentration. Forced air was introduced directly into the column. The airflow rate was maintained 15 l/min for each experimental set. The pH levels were maintained 10.5 for each experiment to convert the ammonium ion to ammonia gas by adding Calcium Oxide. As the pump capacity was fixed, different air to liquid flow ratio was maintained by changing the water flow rates. A hand- operated valve was used to regulate the wastewater flow rate. The effect of pH over 10.5, air-water flow ratio, nature of packing materials and height of materials and initial influent concentration of ammonia on air stripping unit were investigated.

An attempt has been made to find out the stripping constant. For each combination of airflow rate, water flow rate and effluent concentration, the fraction remaining after stripping was calculated by dividing the effluent concentration by the influent concentration. The

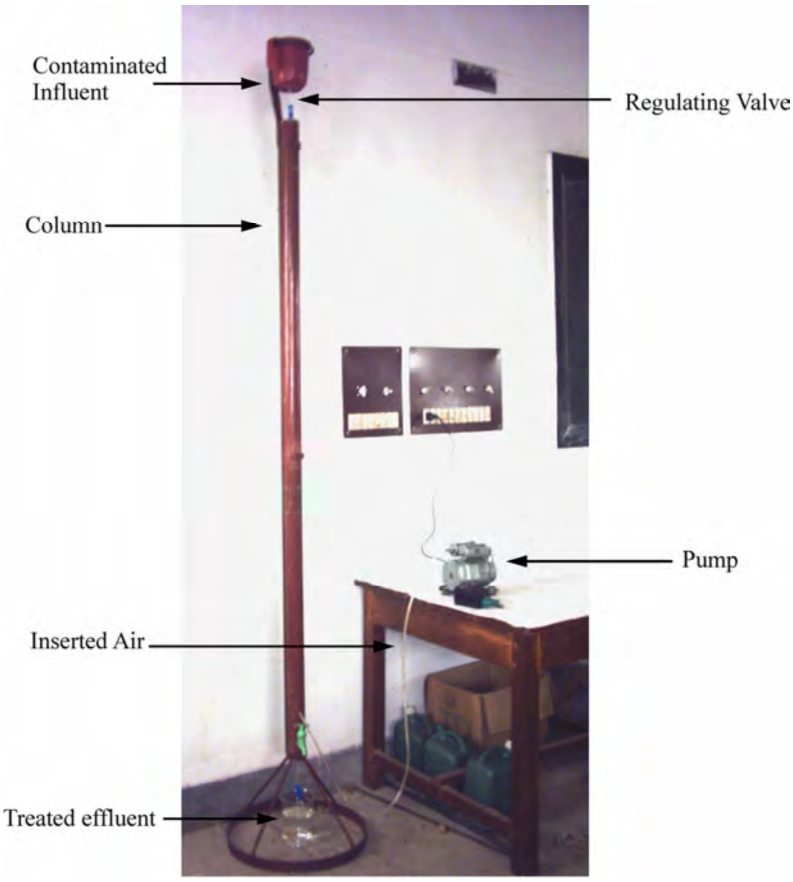

Figure 1. Air stripping experiment (Laboratory setup).

Figure 2. Different types of materials used as packing materials.

fractional results were plotted on log scale against the volumetric air-to-water ratio. An exponential curve was fitted to the data. When there is no airflow, the stripping factor is zero; the effluent concentration should theoretically be equal to the influent concentration. Therefore, the y- intercept should be one. So the curve fit was forced through it. Empirically derived stripping constants were obtained from the exponential equations of the curve fitted lines

The stripping constants can be used to predict treatment performance. The first-order decay model was used to determine stripping constant:

$$Ce/Ci = e^{-Kq} \quad \textbf{(3)}$$

Ce = effluent water concentration
Ci = influent water concentration
K = stripping constant
q = volumetric air-to-water ratio

Digital pH meter (HANNA, HI 98204) was used for the determination of pH. The ammonia was determined by DR-4000 spectrophotometer UV- visible wavelengths at λ=425 nm (Nessler method, using Nessler reagent, Mineral Stabilizer and Polyvinyl Alcohol Dispersing Agent, Hach 8038).

4. Result

4.1. Effect of Packing Height

Packing height has a great influence on stripping process. Laboratory experiments show that removal efficiency increased with the increase of packing height due to the increment of contact time between air and water. Without packing materials, with a constant air-water ratio 2000, the removal was found around 50%. pH of the wastewater was adjusted to 10.5. In case of plastic ring, only 63.59% removal was found for 1 feet height of packing materials and removal efficiency was being gradually increased and gave 91.60% removal for 5 feet height. Same results were found for other three materials. Coal, stone chips, and wood chips gave 60.89%, 60.73% and 60.43% removal for 1 feet height and 87.82%, 85.24% and 84.5% removal for 5 feet height respectively. The effect of packing height for various packing materials has been shown in figure 3.

4.2. Effect of pH on Air Stripping

Above pH 10.5, the effectiveness of the stripping has been studied. The effect of pH on the ammonia removal efficiency of the air-stripping method is shown in figure 4. The best result obtained from the study was 88.94%, 94.15%, 87.8% and 87.4% ammonia reduction by coal chips, plastic ring, stone chips and wood chips respectively at or over pH 11.5. Above pH 10.5, the ammonia removal efficiency was not greatly influenced by pH. For example, in case of coal as a packing material at pH 10.5 with an air flow rate 15 l/min, 87.8 % removal efficiency

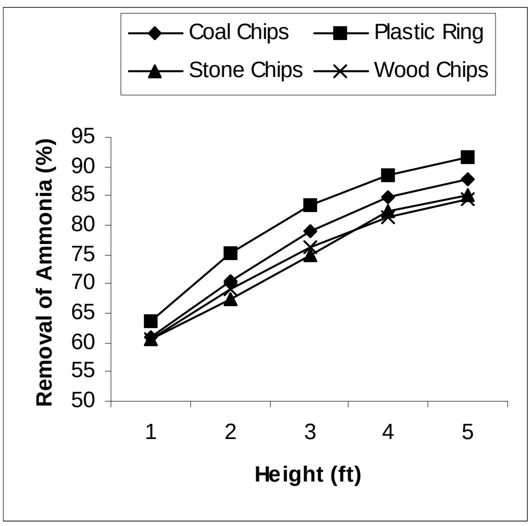

Figure 3. Effect of packing height on removal of ammonia.

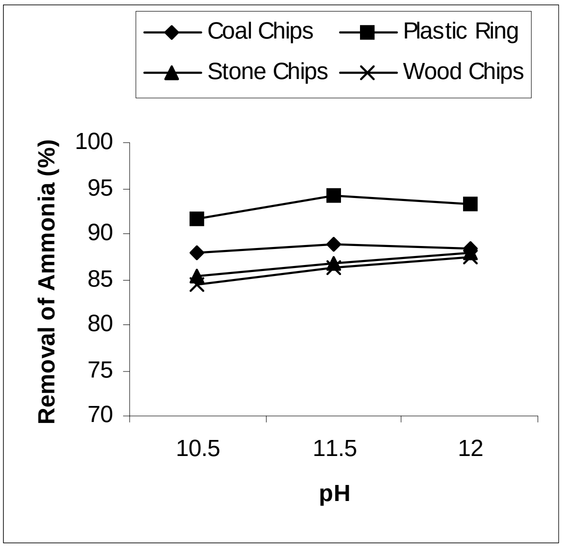

Figure 4. Effect of pH on removal of ammonia.

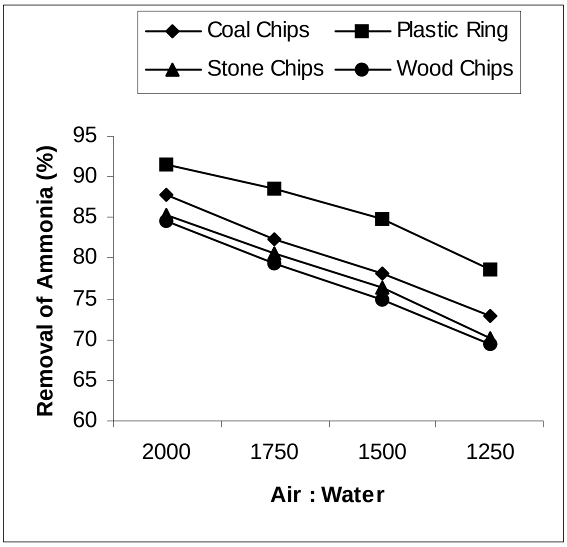

Figure 5. Effect of Air-Water ratio on removal of ammonia.

was achieved, while at pH 11.5 with the same air flow rate 88.9% removal was achieved. But it is evident from the experiment that more calcium oxide is required to raise the pH 11.5 than pH 10.5. Such large additions of lime would increase the formation of heavy calcium carbonate scale within the stripping tower and as a result the efficiency of the system would decrease and severe maintenance problem would occur [15]. How ever, since the effects of pH on removal efficiency were not found to be significant at levels above pH 10.5, there appears to be some reason for raising the level any higher.

4.3. Effect of Air-Water Ratio

The effect of air-water ratio on removal efficiency is presented in figure 5. All the results show very high levels of ammonia removal. An increase of air to water flow ratio from 1250 to 2000 (air flow is constant) facilitated the stripping process. In case of coal, plastic ring, stone and wood chips; removal efficiency was increased from 72.84% to 87.82%, 78.7% to 91.60%, 70% to 85.3% and 69.5% to 84.5% respectively by increasing the air to water flow ratio 1250 to 2000. In all the cases, packing depth was 5 feet and pH was adjusted to 10.5.

4.4. Effect of Initial Concentration

Effect of initial concentration on stripping unit was investigated. Influent concentration was varied from 80 mg/L to 1574 mg/L. In case of coal, plastic ring, stone and wood chips the removal efficiencies were in the range of 86.21% to 91.76%, 90.43% to 92.39%, 80% to 88.31%, and 83.72% to 88.20% respectively. Air to water flow ratio was maintained 2000 and packing depth in all the cases were 5 feet and pH was adjusted to 10.5. The detail results have been shown in table 1.

4.5. Effect of Packing Materials

Quality of packing materials has an influence over efficiency of stripping column. Among the four types of packing materials used as packing materials, plastic ring

Table 1. Effect of influent concentration on air stripping unit.

Coal Chips		Plastic ring		Stone chips		Wood Chips	
Initial Concentration (mg/L)	Final Concentration (mg/L)	Initial Concentration (mg/L)	Final Concentration (mg/L)	Initial Concentration (mg/L)	Final Concentration (mg/L)	Initial Concentration (mg/L)	Final Concentration (mg/L)
1429	174	1574	132	1328	196	1368	212
708	72	752	72	654	82	682	97
348	48	368	28	325	38	356	42
169	17	178	15	164	24	168	22
85	7	87	8	80	16	86	14

gave the best performance due to its high surface area. Among the other three materials, coal gave comparatively better performance. It may be due to its adsorbing property. Wood as packing materials was not found suitable because they amalgamated with each other within a very short time and reduced the surface area. Stone is a heavy material. So it will increase the cost of the building of column. Coal chips may be a good option. It gives good performance. But the major drawback is its self-weight. Plastic ring will be the best choice to use as packing materials. It is lighter, gave the maximum surface area and can be produced locally. Air strippers often become fouled from iron, calcium, manganese, or biological growth. Packed-column air strippers must either have the packing removed for cleaning or be washed with an acid solution [16].

4.6. Effluent Concentration Prediction

The first-order decay model was used to determine stripping constant according to the Equation (1). Stripping constant was found .001, .0014, .001 and .0009 for coal, plastic ring, stone chips and wood chips respectively. The equation with the empirically derived stripping constants was used to predict effluent water concentration. To verify the prediction model, some known concentration of ammonia contaminated Wastewater was passed through the air-stripping unit by keeping the air-water ratio 2000. A curve of experimental concentration vs. predicted concentration has been plotted in figure 6 to evaluate the accuracy of the model. From the model prediction curves, Equation (4), (5), (6) and (7) have been generated to find out the value of effluent concentration of ammonia when the packing materials are coal, plastic ring, stone chips and wood chips respectively. Those equations will be valid only when the pH of the raw water is adjusted to 10.5 and the height of the packing materials is 5 feet.

$$Ce = Ci\ e^{-.001q} \quad \textbf{(4)}$$

$$Ce = Ci\ e^{-.0014q} \quad \textbf{(5)}$$

$$Ce = Ci\ e^{-.001q} \quad \textbf{(6)}$$

$$Ce = Ci\ e^{-.0009q} \quad \textbf{(7)}$$

Where

Ce = effluent water concentration

Ci = influent water concentration

q = volumetric air-to-water ratio

4.7. Ammonia in the Air

In air stripping unit, wastewater is treated and becomes free from ammonia. But it posses a great threat to the ambient air. Huge amount of ammonia (828 to 1401 ppm) has been found at the outlet of the stripping unit by using mass balance equation. Recovery of ammonia as either ammonium sulfate or nitrate by scrubbing with sulfuric or nitric acid can be a solution [17].

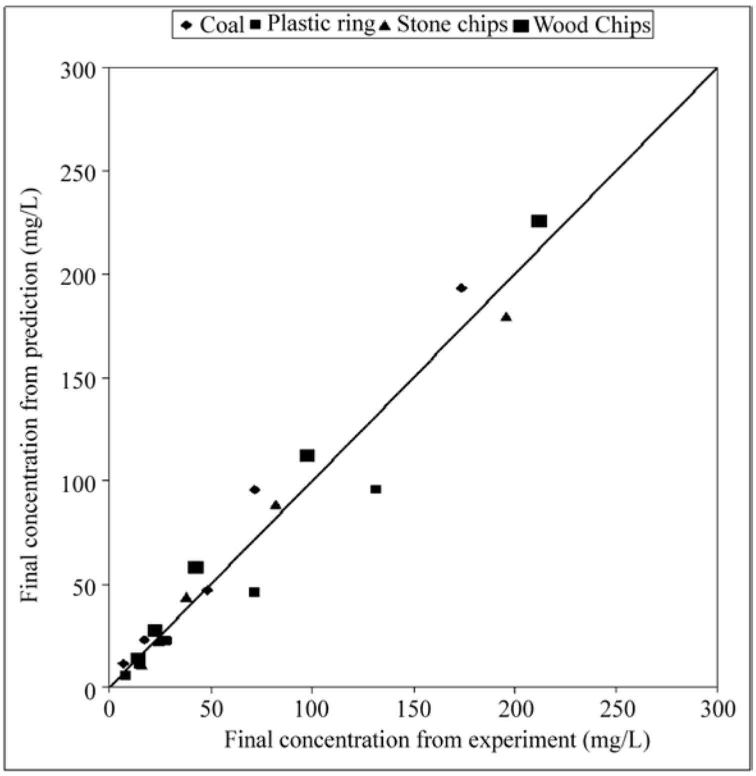

Figure 6. Verification of predicted model.

5. Conclusion

Air-stripping method achieved very high rates of ammonia removal and the results indicated that it could be a great solution for wastewater treatment of NGFFL. Its use requires a large addition of lime (approximately 2 to 3 gm per liter of wastewater; amount is not fixed as the alkalinity of the wastewater was found to vary), a high airflow rate (NGFFL uses huge amount of air to generate fertilizer. They can transfer air through a bypass line to the air-stripping unit.) and the provision of a tower containing some packing materials. Different materials were used as packing materials. Best result was found using plastic ring for its higher surface area. It can be produced locally by using 1/2″ PVC pipe and it is relatively cheap in Bangladesh.

6. References

[1] ESCAP, "Private enterprise development for export promotion in south Asia," United Nations Economic And Social Council, Fourteenth meeting 2–4, December 2002.

[2] M. N. A. Khan, P. Datta, A. S. M. Dakua, and S. I., "An assessment of Water Quality Deterioration of the River Kushiara due to Effluent Discharge from Natural Gas Fertilizer Factory," B. Sc. Engg. Thesis, CEE Dept, Shah Jalal University of Science & Tech., Sylhet., 2002.

[3] USEPA, "Agency Quality Criteria for Water," EPA # 440/5-86-001, US Environmental Protection Agency, Washington, DC. 1986.

[4] DOE, "The Environment Conservation Rules," Department of Environment, Ministry of Environment and Forest, Government of the People's Republic of Bangladesh, 1997.

[5] U. Dhar and M. Rahman, "Surface water quality modeling: A case study on Kushiara River," B.Sc. Engg. Thesis, CEE Dept, Shah Jalal University of Science & Tech., Sylhet, 2006.

[6] M. Kavanaugh, and R. R. Trussell, "Design of aeration towers to strip volatile contaminants from drinking water," Journal AWWA, pp. 684–692, December 1980.

[7] H. Shulka, and R. E. Hicks, "Process design manual for stripping of organics," EPA- 600/2- 84-139, 1984.

[8] E. Mead and J. Leibbert, "A comparison of packed -column and low-profile sieve tray air strippers," Proceedings of the 1998 Conference on Hazardous Waste Research, 1998.

[9] W. Ball, M. D. Jones, and M. C. Kavanaugh, "Mass transfer of volatile organic compounds in packed tower aeration," J. Water Pollution Control Federation, Vol. 56, No. 2, pp. 127–136, 1984.

[10] J. M. Montgomery, Consulting Engineers Inc., "Water treatment principles & design," John Wiley & Sons, New York, pp. 237–261, 1985.

[11] R. Treybal, "Mass-transfer operations," McGraw-Hill, New York, 3rd ed., pp. 275–313, 1980.

[12] L. Culp, Wesner, M. George and L. Culp, "Handbook of advanced wastewater treatment," 2nd ed., Van Nostrand Reinhold Co., New York, 1978.

[13] P. H. Liao, A. Chen and K. V. Lo, "Removal of nitrogen from swine manure wastewaters by ammonia stripping," Bioresource Technology 54, Elsevier Science Limited, Great Britain, pp. 17–20, 1995.

[14] USEPA, "Wastewater technology fact sheet ammonia stripping," EPA 832-F-00-019 US Environmental Protection Agency, Washington, D. C., 2000.

[15] USEPA, "Nitrogen removal by ammonia stripping," EPA/670/2-73-040, US Environmental Protection Agency, Washington, D. C., 1973.

[16] Jaeger Products, Inc., 1611 Peachleaf, Houston, TX 77039, jpadmin@jaeger.com/1006foul.htm.

[17] S. C. Bhatia, "Environmental pollution and control in chemical process industries," Khanna Publishers, Delhi, pp. 644–651, 2001.

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Impact of Irrigation on Food Security in Bangladesh for the Past Three Decades

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Abstract

Bangladesh has made impressive progress in agriculture sector in the last three decades and has almost become self-sufficient in food grain production. This is a tremendous achievement owing to its small territory and huge population and this was achieved through agricultural mechanization and modernization. Irrigation is one of the leading inputs has direct influence to increase yield, food grains production and plays vital role for ensuring food security in Bangladesh. The present study examined the growth of irrigated area and its impact on food grain production during last three decades. Time series data were used for the study. Different statistical methods such as mean, percentage, linear and exponential growth model were applied for getting meaningful findings. Various technologies have been used for irrigating crops which have contributed to rapid expansion of irrigated area. The conventional irrigation methods (Low Lift Pump, Dhone, Swing Basket, Treadle Pump etc.) were replaced by modern methods (i.e Deep Tube Well and Shallow Tube Well). In addition, surface water irrigation also sharply declined, losing its importance due to lack of new surface irrigation project and the ineffectiveness of earlier project. Groundwater covered 77 percent of total irrigated area and major (62%) extractions occurred through Shallow Tube Wells (STWs). The rapid expansion of ground water irrigation in respect to STWs irrigation was due to government's withdrawal on restrictions on tube well setting rule, encouraging private sector and the cost effectiveness of Chinese engine which have been affordable to the small and medium farmers. Irrigated area thus, increased by about three times and cropping intensity also increased from 154 to 176 percent. *Boro rice*, an irrigated crop, consumed 73 percent of the total crop irrigation and contributed to a greater extent in total rice production in Bangladesh. *Boro* rice alone contributed to 55 percent of total food grain and was also highest (3.44 MT per hectare) compared to *aus rice* (1.66 MT per hectare) and *aman rice* (1.99 MT per hectare) per unit production. Consequently, the cultivated area of *boro rice* increased by 1168 to 4068 thousand hectares. The higher productivity of *boro* rice has almost helped the nation to meet her food requirements (about 24 Million MT). *Boro* rice production was highly correlated (r = .978) with irrigated area. Expansion of one hectare of irrigated area added 3.22 MT of *boro* rice in Bangladesh. Finally, the study suggested for expansion of irrigated areas (ground water and surface water), adoption of modern technologies and formulation of farmers' friendly policy.

Keywords: Irrigation, Food Security, Boro Rice and food Grain Production

1. Introduction

South Asia is a home of 1.5 billion people most of which live in India and Bangladesh. Bangladesh, the most densely populated country in the world has been suffering from food deficiency for a long time. Food scarcity has remained the major challenge for the government since liberation (Independence, 1971) as it tries to increase food grain production to meet the demands of the nation's growing population. Since the economy of an agrarian society (like Bangladesh) is dominated by agriculture and the livelihoods of the farmers are largely connected with intensive agriculture production. Food grain occupies the lion's share of agricultural GDP and it employs about 60 per cent of total labour force [1]. Hence, any internal and external threat (social, political, natural and environmental) to agriculture directly affects food grain production as well as food security of the country.

Food security is defined as access to enough and safe food by all people at all times for maintaining an active and healthy life. Aggregate domestic production and per capita availability of food grains increased in the country over the past decades. But the country still depends on import of food grains (in 2007-08 imported 11.5 percent of total availability) [2]. Therefore, it is timely demand to explore the domestic potentiality and to increase production for attaining the Millennium Development Goal (MDG goal is to reduce the extreme poverty to half by 2015 ensuring food as basic requirements).

Rice is staple food of Bangladeshi people and it constituted about 90% of the total food grain production [3]. Of the three types of rice *aus*[1], *aman*[2] and *boro*[3], the *Boro* rice alone contributed the highest share of total rice production since 1998-99 to date [4]. Therefore, increase of *Boro* rice production would be a significant possible way to overcome food deficiency in the country. *Boro* rice is produced in *Rabi* season (October to March) and it grows totally under irrigated condition. Thus, development of irrigation availability is playing a vital role in this regard.

There are two major sources of irrigation in Bangladesh-surface and ground water. Low Lift pump (LLP), Canal and Traditional (Dhone and Swing basket) are used as a means of technology for surface water irrigation while Deep Tube Wells (DTW)[4], Shallow Tube Wells (STW)[5] and Hand Tube wells are used for ground water irrigation. Before70s, irrigation was mainly dependent on surface sources and in the mid-seventies government emphasised on groundwater irrigation with DTW projects. But government soon shifted to STW because of it's suitability to socio-economic status of the farmers (less investment cost, small land holdings, availability in the market, withdrawing restriction on import and STWs spacing) and STWs enclosed 62 per cent of total irrigated area [5]. The total irrigation coverage was increased 1726 to 5898 thousand hectare within the period of 1981-82 to 2006-07 (342 per cent) whereas irrigation potential is estimated at 7,550 thousand hectares [6]. There is still possibility to expand 28 percent of irrigated area according to irrigation potentiality. At present groundwater contributes to 77 percent of total irrigated area in Bangladesh [5].

About 80 percent of groundwater was used for crop production in which *Boro* paddy consumed 73 percent of total irrigation [7]. Hence, *Boro* rice production is increasing at about 1% annually and contributes to 55% of the total rice production [8]. The application of groundwater irrigation increased with the introduction of High Yielding Variety (HYV) seeds to meet the food requirements of a growing population [9]. In contrast the yield potential of the existing HYV rice is more than 4 MT/ha., whereas the average yield realized by the majority of farmers is less than 3.0 MT/ha [2]. Thus, on farm research is important to reduce the production gap. In addition groundwater-based irrigation economy is crucial for increasing domestic production, attaining food security and lifting millions of poor farmers out of poverty. Hence, this paper intends to acquire an integrated understanding of the importance of irrigation, its impacts on food grain production and rural livelihoods and also the role of existing policy and institutional guidance.

[1,2]Mostly rain fed rice, [3]Irrigated rice, [4]The discharge capacity of deep tube wells are about 50 lt/sec having greater depths (upto 100-120m) and larger diameter compared to shallow wells. [5]Shallow Tube wells are small irrigation wells having discharge capacities of 12-15 lt/sec with maximum depths of 40-60m and well diameter of 100-150mm.

2. Methodology

The present paper is mainly based on secondary sources of information. Data were collected from Bangladesh Bureau of Statistics (BBS) in the period of 1980-81 to 2006-07. Moreover, Bangladesh Agricultural Development Corporation (BADC), published articles, Economic Review, and Fifth Five Year Plan was also taken as a crucial source of data. After collecting necessary (time series) data, they were analysed using tabular, graphical and econometric techniques. Microsoft Excel and SPSS program was applied for analysing data in a meaningful way. Both linear and exponential equations were used for representing time series data. The equations are as follows-

$$Y_e = a + bt \quad \textbf{(1)}$$

and

$$Y_e = Ae^{bt}, \quad \textbf{(2)}$$

after taking log the equation is- $\log Y_e = \log A + bt$
Y_e = dependent variables
a= intercept
b= Co-efficient
t= time series

3. Development of Irrigation Technologies and Cropping Intensity

At the initial stage of irrigation development, the main emphasis was on low lift pump for extracting surface water and later on, Bangladesh Agricultural Development Corporation (BADC) initiated capital-intensive methods for DTW installation in Bangladesh and provided subsidized well components (pumps, drilling equipment, etc.) for rapid expansion of larger public groundwater irrigation schemes (1960s started from Thakurgoan area, north-western part of Bangladesh). Privatization and expansion of minor irrigation and withdrawal of Government subsidy in irrigation equipment lead to tremendous development of STWs during last two decades [10]. The percentage contribution of different irrigation technologies is shown in Table 1. Table 1 depicts that the uses of surface irrigation drastically reduced while groundwater irrigation technologies increased significantly.

Modern irrigation mainly consists of DTW and STW which have almost entirely replaced the pioneer Low Lift Pump (LLPs) and at the same time DTWs is gradually loosing its application as it is economically and socially inappropriate [11]. The share of surface water irrigation technologies (LLP) reduced by 41 to 16 percent of total irrigated area during 1981-82 to 2006-07. Again the traditional (i.e dhone, swing basket etc) and canal irrigation coverage sharply declined to about 10 percent (canal 3 percent and traditional 7 percent). On the other hand, ground water irrigation increased significantly particularly due to rapid expansion of STWs technologies. In early 90s the STW and DTW irrigation covered 37 and 24 percent of total irrigated area respectively. Within two decades, STWs occupied 62 percent of total irrigated area while DTW irrigation coverage was only 14 percent. This indicated that small farmers' share on STW ownership has increased significantly over the years in Bangladesh because of less investment cost, easy installation, easy maintenance and can be shared among small groups of farmers, convenient for small landholding owners and withdrawal of import restrictions [12]. It appears from Table 1 that the percentage of irrigated area increased over time. In 1981-82 total irrigated area was 16 percent whereas in 2006-07 it observed 56 of total cultivated area.

Table 1. Percentage of irrigated area by various technologies in Bangladesh.

Year	DTW	STW	LPP	Canal	Traditional	Others	Total irrigated area ('000) hectare	Total cultivated area ('000 ha.)	Percentages of irrigated area	Cropping intensity
1981-82	15.7*		40.8	9.5	25.6	8.4	1726	10491	16	153.70
1985-86	45.9*		29.0	7.8	12.1	5.2	2098	10447	20	154.47
1991-92	20.3	37.4	22.3	5.7	13.1	1.2	3028	10249	32	171.81
1995-96	19.1	46.3	19.1	4.3	10.3	1	3554	9946	36	173.18
2001-02	14.74	56.39	16.71	3.54	7.04	0.6	4598	10665	43	176.94
2004-05	14.24	59.60	15.93	-	9.70	0.53	5037	10373	49	176.85
2005-06	14.29	61.77	15.31	-	7.72	0.39	5604	10534	53	175.96
2006-07	13.82	61.80	16.27	-	7.12	0.37	5898	10579	56	176.07

* Indicates both STW and DTW percentages

Table 2. Shows the rice requirements and availability in domestic sources and also external sources during 1991-92 to 2006-07.

Year	Production ('000MT)			Total rice production/ availability ('000MT)	Total requirement ('000 MT)	Gap	Food availability gm/cap/day	External sources aid + import ('000MT)
	Aus	Aman	Boro					
1991-92	2179	9269	6804	18252	18710	-458	454	-
1992-93	2075	9680	6586	18341	19040	-699	445	1183
1993-94	1850	9419	6772	18041	19370	-1329	440	966
1994-95	1791	8504	6538	16833	19700	-2867	428	2568
1995-96	1676	8790	7221	17687	20030	-2343	439	2427
1996-97	1871	9552	7460	18883	20360	-1477	430	967
1997-98	1875	8850	8137	18862	20690	-1828	455	1951
1998-99	1617	7736	10552	19905	21040	-1135	522	5491
1999-00	1734	10306	11027	23067	21380	1687	514	2104
2000-01	1916	11249	11921	25086	21510	3575	545	1554
2001-02	1808	10726	11766	24300	21790	2510	521	1798
2002-03	1850	11115	12222	25187	22090	3097	564	3220
2003-04	1832	11520	12838	26190	22380	3810	554	2788
2004-05	1500	9819	13837	25156	22680	2476	539	3374
2005-06	1745	10810	13975	26530	23010	3520	534	2459
2006-07	1512	10841	14965	27318	23250	4068	540	1440

The cropping intensity is determined as the ratio of total cropped area of multiple crops within a year to net cultivated area, which is expressed in terms of percentage. Farmers typically grow one or two crops per year and leave their lands fallow for rest of the time. The cropping intensity increased by 154 to 176 percent within the period of 1981-82 to 2006-07 (Table 1), while in some regions it was about 200 percent (Bogra and Comilla district). The rapid boost of cropping intensity was possible due to expansion of irrigated area and development of irrigation technologies in Bangladesh.

4. Food Requirements and Availability

It is observed that from 1991-92 towards 1998-99 there were deficit in rice production and the deficit ranged from 458 to 2867 thousand metric tons.

Later, the country reached to a marginally self-sufficient in rice production and it exceeded the country's total requirement of about 1600 to 4000 thousand metric tons. In reality the country with this small amount of surplus production is in a vulnerable situation as it is always threatened by frequent disasters like drought, flood, cyclone and sidr etc, which causes damage to the country's valued rice crops almost every year [1]. As a result, the government has to seek for foreign aid and import every year to make food reserve as buffer stock (Table 2). The amount of import and foreign aid varies according to extent of natural calamity and domestic production. The external sources of food was highest (5491 thousand MT) in 1998-99 as country was severely affected by flood. *Boro* rice usually, is less affected by natural disaster and consequently occupied largest share (55 percent in 2006-07) of total rice production. Moreover, 98 percent of *boro* rice is HYV and produced under irrigated condition.

5. Trends of Rice Production in Bangladesh

Within the crop sub-sector, food grains particularly the rice dominates in respect to both cropped area and production [13]. The following Figure 1 shows the trend of rice production in Bangladesh during 1980-81 to 2005-06. The production of *aus* rice was decreased while *aman* and *boro* rice was increased over the period of 1981–82 to 2005–06. Again, the fluctuation of *aman* rice as well as *aus* rice production was common due to the above named disasters and natural calamities. In 1988-89, 1998-99 and 2004–05 production year, a*man* rice production was drastically fall because of devastating flood all over the country (Figure 1). In such circumstances, people rely on *boro* rice production and they provide full efforts to overcome the crisis. *Boro* rice compensated the deficits because of its less reliant on nature and varietal improvement. Moreover, effective implementation of rehabilitation programs by the government and timely supply of inputs including irrigation equipments was also another reason of success. The R^2 value was higher for *boro* rice production than *aman* rice production.

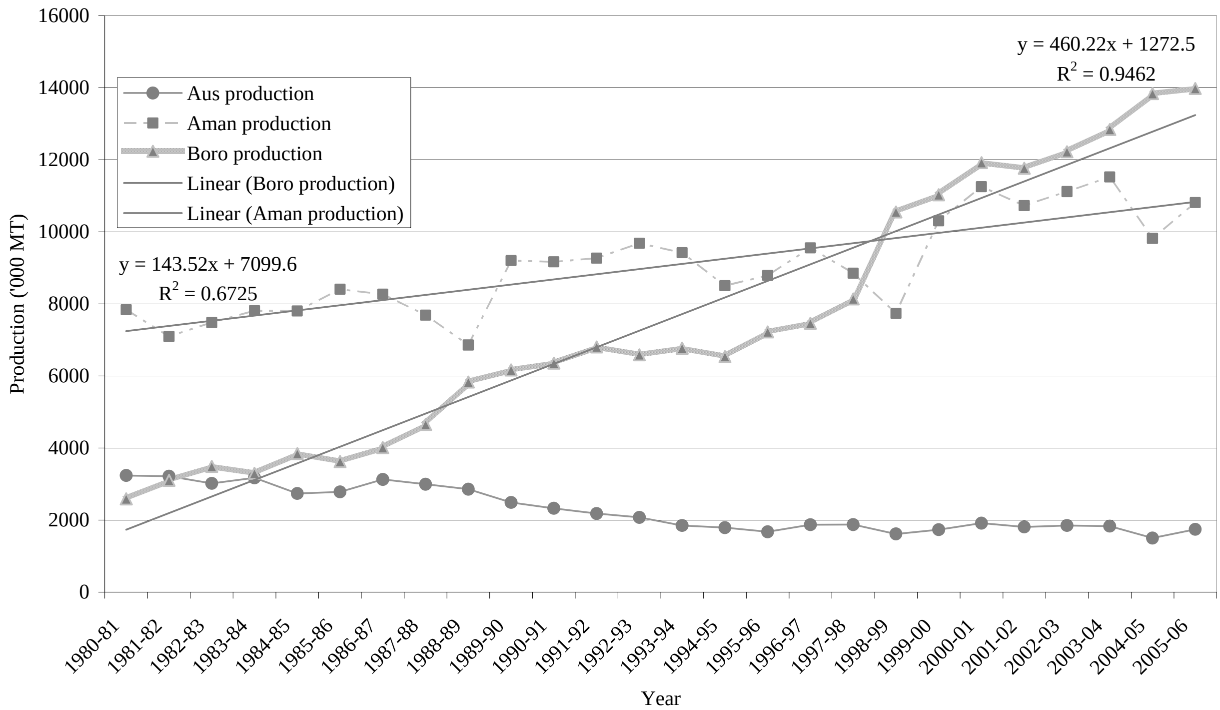


Figure 1. Trend of aus, aman and boro rice production in Bangladesh.

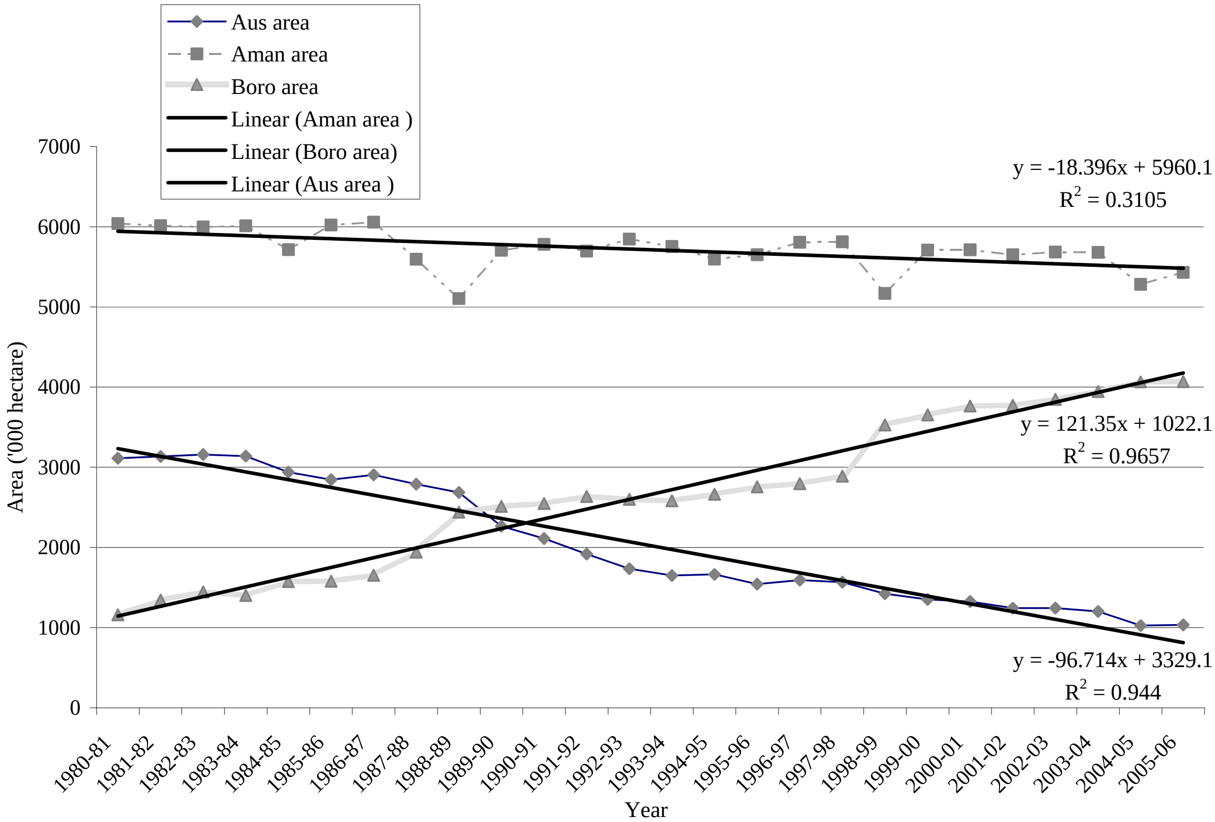


Figure 2. Trend of aus, aman and boro cultivated area in Bangladesh.

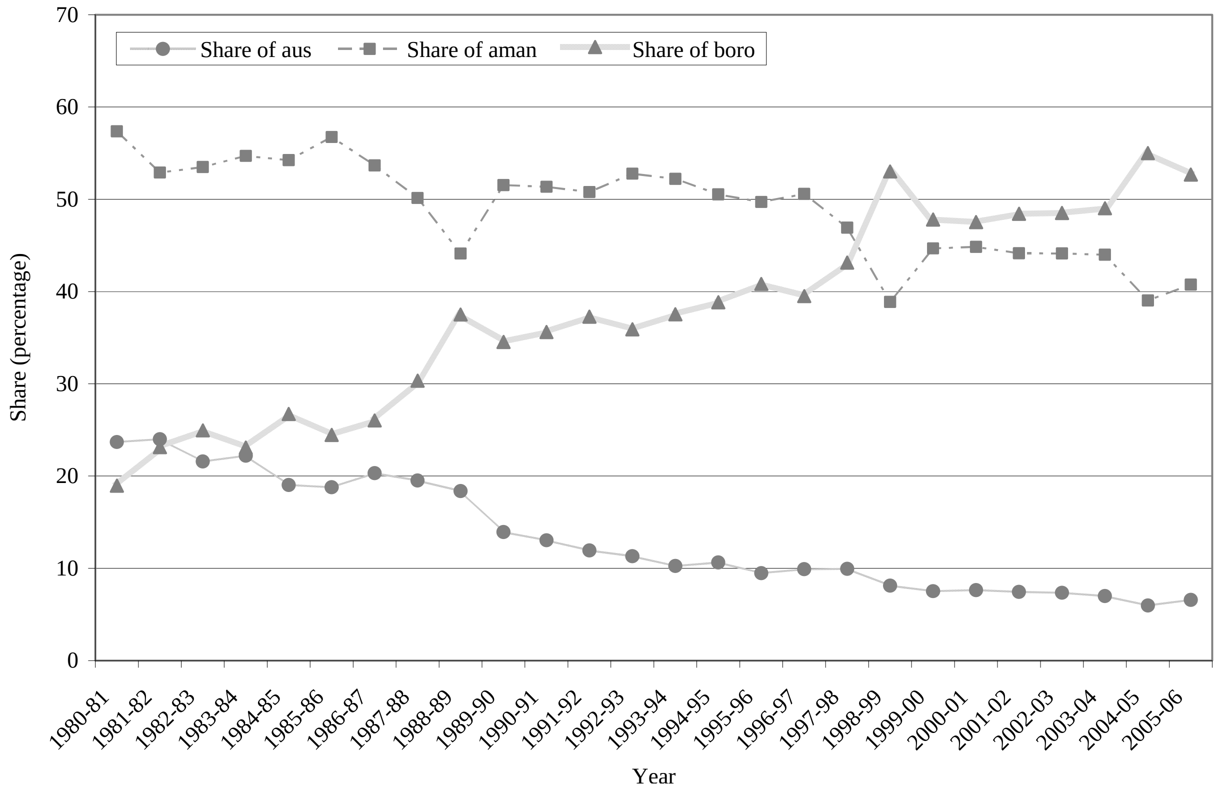


Figure 3. Percentage of aus, aman and boro production of total rice production in Bangladesh.

6. Trend of Rice Cultivated Area in Bangladesh

At present, rice covers 75 percent of total cultivable land in Bangladesh [5]. Figure 2 depicts the trend of different rice cultivated area during 1980-81 to 2005-06. It is interesting that most of *aus* rice cultivated areas were occupied by *boro* rice while *aman* cultivated area slightly declined over the time. It might be the reason of relatively less varietal improvement of *aus* and *aman* rice than *boro* rice and seasonal calamity. In the year of 1980-81 the *boro* cultivated area was 1161 thousand hectares and it was increased by 4068 thousand hectares after three decades of irrigation development while *aus* rice production area decreased by 3113 to 1035 thousand hectares within this period of time. On the other hand, *aman* cultivated area declined but still its occupied higher area than others. The fluctuation of *aman* cultivated area was also observed particularly in the natural disadvantaged years.

7. Contribution of *Boro* Rice to Total Rice Production

Boro rice is relatively free from weather hazard as it is grows in winter season. As a result, quick adoption of *boro* rice by the farmers' remarkably increased which made a substantial contribution to food grain production as well as agricultural development as a whole in Bangladesh [14]. The share of total rice production in different types of rice for the period of 1980-81 to 2005-06 is shown in Figure 3. At the initial stage of irrigation technology development, *Boro* rice contribution was lowest among different seasonal rice (*aus* and *aman*) but it is occupying the highest position since 1998-99 to date. In 1980-81 *aman* rice dominated and contributed to 57 percent of total rice production while *aus* and *boro* rice contribution was only 24 and 19 percent respectively. Figure 3 show that *boro* rice contribution to total rice production was in an increasing trend and increased by 55 percent in 2004-05 from 19 percent in 1980-81. Meanwhile *aus* rice contribution decreased at a greater length which could be due to traditional cultivation method, less varietal improvement and its replacement by *boro* rice.

8. Per Hectare Yield of Different Seasonal Rice

The average rice yield of Bangladesh is lower than in Asian countries like India, China [7]. Figure 4 shows per hectare yield of *aus*, *aman* and *boro* rice during 1980-81 to 2005-06. However, it was noted that all kind of rice yield was in an increasing trend and the gap between *aus* and *aman* rice yield was more or less similar. But the *boro* rice yield was about two and three times higher than *aman* and *aus* rice respectively. The major reason behind such differences observed was because *boro* rice

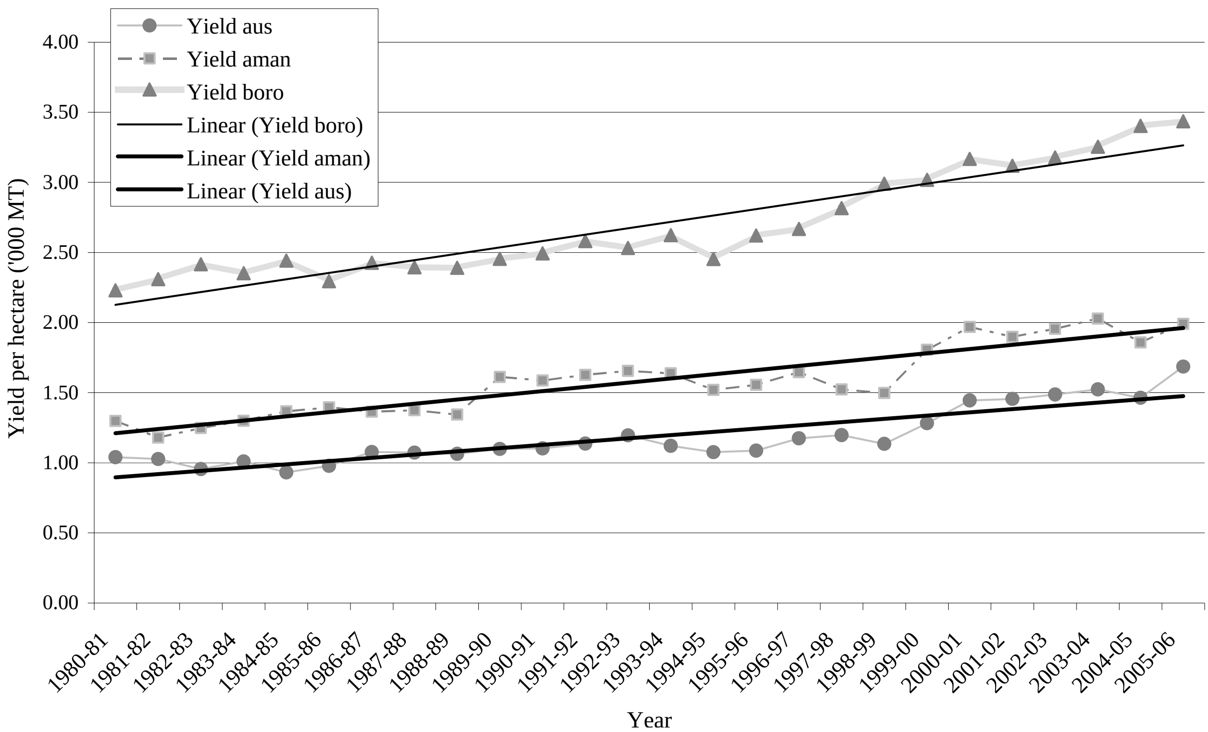
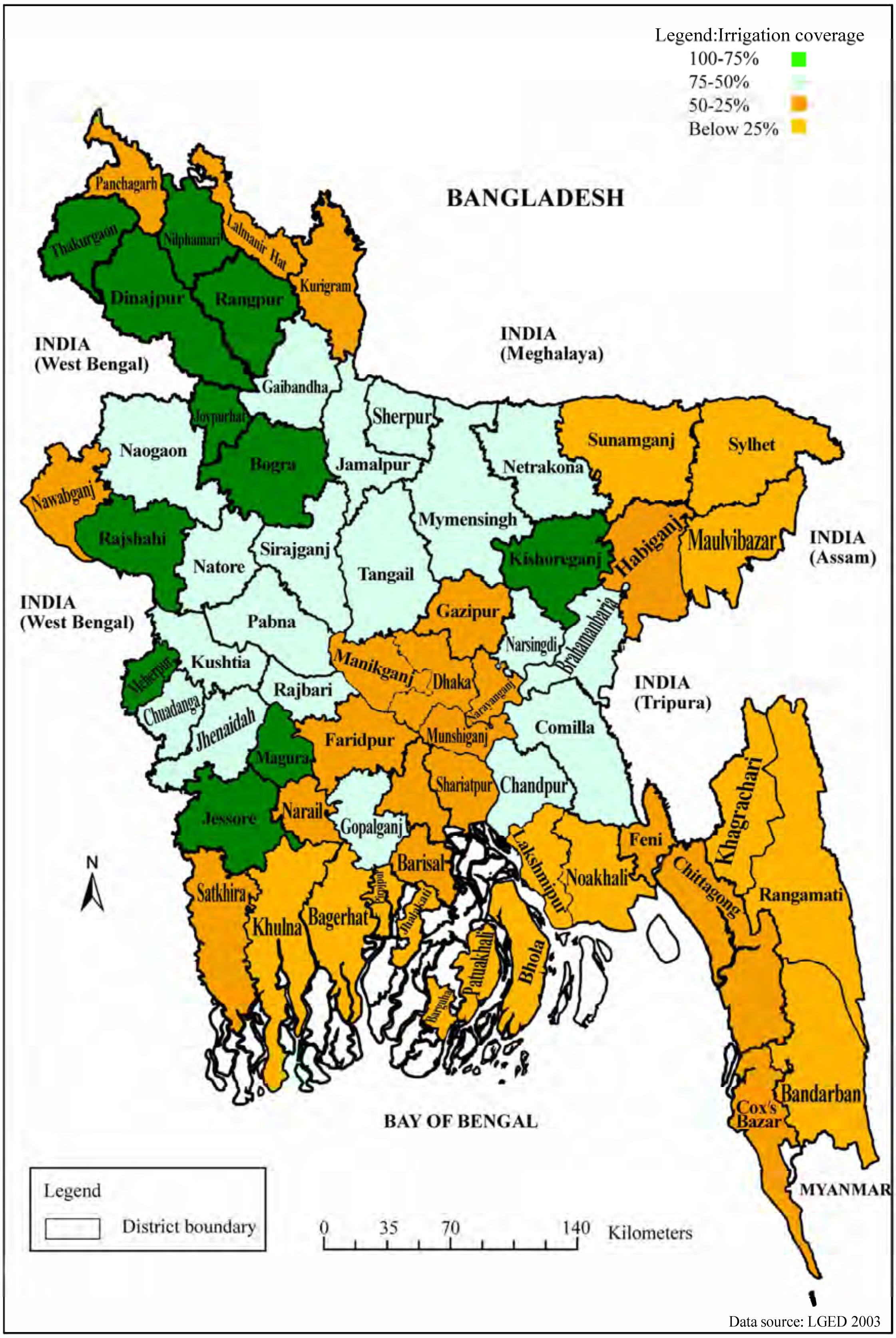


Figure 4. Per hectare yield of aus, aman and boro during 1980-81 to 2005-06 in Bangladesh.



Map 1. Percentages of irrigation in different region of Bangladesh.

varieties (97 percent) were High Yielding Variety (HYV) while it was less common for *aus* and *aman* rice. Figure 4 represent that though per hectare production increased till (2005-06), it did not exceed 2 MT/ha. for *aus* and *aman* rice yield whereas *boro* rice yield was about 2 MT/ha. in 1980-81 (the initial stage of groundwater irrigation) its yield increased by 65 percent (2.23 MT/ha. in 1980-81 and 3.44 MT/ha. in 2005-06) during last three decades.

9. Irrigation Coverage in Different Region

Irrigation coverage is not equally distributed all over the country because of different topography, availability of modern irrigation technology and socio-economic status of farmers. Map 1 shows the percentages of irrigation coverage in different region of Bangladesh in the production year of 2007-08. Four colours used to indicate the extent of irrigated area in different regions. It is observed that percentage of irrigated area was highest (green colour, 100-75 percent) which constituted 11 districts out of 64 districts and mostly situated in the north and north-western part of the country. There were also 19 districts moderately irrigated (75-50 percent mentioned as sky colour) composing upper middle and mid eastern part of the country. Another 19 districts were 50-25 percent under irrigated condition constituted in the middle and lower part of the country. Remaining 15 districts mostly situated in the hilly and coastal belt of the country had less irrigation coverage (below 25 percent). In recent time government has taken some initiative to expand irrigated area in the coastal belt by protecting coastal water resources [15].

10. Relationship of Different Parameters

10.1. Area and Production

Following Table 3 shows the relationship between cultivated area and production of different rice in Bangladesh.

It can be observed from table 3 that *boro* rice production was highly correlated (r=0.986) with cultivated area while *aman* rice production was negatively related. *Aus* rice production was also statistically significant at 1 percent level with cultivated area at a value of 0.703 which indicated strong correlation. The R^2 value of linear model was .943, .012 and .972 for *aus*, *aman* and *boro* respectively which implied that independent variables (cultivated area) could explain 94, 1 and 97 percent of dependent variable (production) of *aus*, *aman* and *boro* rice respectively. More or less similar results also appeared in exponential growth model.

10.2. Irrigated Area and *Boro* Rice Production

Boro rice is grown on fully irrigated condition therefore, only relationship between *boro* rice production and irrigated area has been examined. The summary of the results are shown in Table 4. The result shows that the increase of one hectare irrigated area added 3.22 MT rice considering *boro* rice production with irrigated area in Bangladesh. In addition R^2 value explained about 96 percent of dependent variable (*boro* rice production) by the independent variable (total irrigated area). Moreover, *Boro* rice production was strongly correlated (r=.986) with total irrigated area in Bangladesh.

Table 3. Relationship between cultivated area and production of rice during 1980-81 to 2005-06.

Type of rice	Linear model				Exponential model				Pearson Correlation (r)
	R^2	Intercept (a)	Coefficient (b)	t	R^2	Intercept (a)	Coefficient (b)	t	
Aus	.943	752.71	.7548	399.45**	.938	1149.48	.0003	365.33**	.703**
Aman	.012	5897.70	-.0206	.596	.008	5865.00	-3.E-06	.661	-.811**
Boro	.972	-2561	3.7764	818.16**	.993	1579	.0005	3406**	.986**

** indicates as 1 percent significant level (2 -tailed)

Table 4. Relationship between irrigated area and *boro* rice production during 1980–81 to 2005-06.

Type of Rice	Linear model				Exponential model				Pearson correlation (r)
	R^2	Intercept (a)	Coefficient (b)	t	R^2	Intercept (a)	Coefficient (b)	t	
Boro rice	.957	-3225.7	3.220	492.01**	.975	1490.70	.0005	870**	.978**

** indicates as 1 percent significant level (2 -tailed)

11. Conclusion and Suggestion for Policy Implication

Irrigation is one of the key factors making the country self-sufficient in food grain production and contributes greatly towards agriculture GDP (Gross Domestic Production). Irrigation particularly ground water irrigation plays an important role for alleviating rural poverty in Bangladesh. It materialized that irrigation technologies are developing and small and medium farmers are involved more in the production process which enhanced their household food security in particular and national food security in general. From findings it appears that ground water irrigation has been given more emphasis from government as well as individual entrepreneur point of view though National Water Policy (NWPo) has highlighted the conjunctive use of surface and ground water [16]. Further more NWPo suggested to ensure the availability of water to all elements of society (poor, unprivileged), accelerating public and private water delivery system encompassing water right, water pricing, efficient water management considering economic efficiency, environmental degradation and climate change. Therefore, it should be given similar or more attention for the development of surface water irrigation in Bangladesh.

The average yield of rice is low especially for *aus* and *aman* rice as compared to Asian countries (India and China) therefore it is of urgent need to increase government investment in research for varietal improvement and on farm water management. Regarding varietal improvement, only 53 percent land was under HYV rice in case of *aus* cultivated area and it was 62 percent for *aman* rice in 2006-07. On the other hand HYV occupied 97 percent of *boro* rice cultivated area in the same year. Thus, there is a greater chance for varietal improvement to increase per unit production.

Increasing one hectare of irrigated area added 3.22 MT *boro* rice production therefore it is highly recommended for expansion of remaining land (28 percent) under irrigated condition for achieving country food requirements. However, there is a concern of arsenic contamination and declining water level due to ground water extraction over 20-30 years [17]. B*oro* rice production should be emphasized due to its less dependence on natural calamity, high varietal improvement (97 percent), and higher per unit production as compared to other seasonal rice (*aus* and, *aman*).

Existing institutions should be strengthened as well as capacity building for sustainable development and management of ground water and surface water irrigation due recent concerns about salinity, declining water level, ground water arsenic contamination, absence of irrigation pricing rules and regulations and power crisis etc. [18].Hence, formulation of “Groundwater and Surface water Act” is necessary for ensuring farmers benefit and long-run sustainability of natural resources. Irrigation has direct influence towards farmer’s socio-economic status therefore; further study could investigate the implication of irrigation on poverty alleviation in rural Bangladesh.

12. References

[1] M. S. Alam, M. R. Islam, M. A. Jabber, M. S. Islam and M. A. Salam, “Institutional backup towards food security in Bangladesh,” In Proceedings BKAS 13th National Conference and Seminar on Climate Changes: Food Security in Bangladesh, Vol. 13, Dhaka, Bangladesh PP, August 2008.

[2] R. K. Talukder, “Food security in Bangladesh: National and global perspectives,” In Proceedings BKAS 13th National Conference and Seminar on Climate Changes: Food Security in Bangladesh, Vol. 13, Dhaka, Bangladesh PP, August 2008.

[3] M. Z. Huda, “Regional development of irrigation technologies and its impact on food grain production in Bangladesh,” MS Thesis, Department of Agricultural Economics, BAU Mymensingh, Bangladesh, 2001.

[4] Bangladesh Economic Review (BER), Bangladesh Economic Survey, 2005, Finance Division, Ministry of Finance, Government of Bangladesh, Dhaka, Bangladesh, 2007.

[5] Bangladesh Bureau of Statistics, Statistical Year, Book of Bangladesh, Bangladesh Bureau of Statistics, Statistics Division, Ministry of planning, Government of People's Republic of Bangladesh, Dhaka, 2008. (http://www. bbs.gov. bd/ agriculture_ wing/ annual _ agri _ stat. pdf)

[6] T. Ernest, “Water profile of Bangladesh,” In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D. C.: Environmental Information Coalition, National Council for Science and the Environment), FAO, 2007.

[7] M. W. Rahman and R. Ahmed, “Shallow tube well irrigation business in Bangladesh,” Paper Presented at Summary and Synthesis Workshop at Kathmandu, Nepal, March 20–24, 2008.

[8] Bangladesh Bureau of Statistics, “Statistical year book of Bangladesh,” Bangladesh Bureau of Statistics, Statistics Division, Ministry of planning, Government of People's Republic of Bangladesh, Dhaka, 2007.

[9] Bangladesh Economic Review, Bangladesh Economic Survey, 2005, Finance Division, Ministry of Finance, Government of Bangladesh, Dhaka, Bangladesh, 2006.

[10] A. Zahid and S. R. U. Ahmed, “Groundwater resources development in Bangladesh: Contribution to irrigation for food security and constraints to sustainability,” Groundwater Governance in Asia Series-1, pp. 25–46, 2006.

[11] R. P. Jones, “Irrigation service market in Bangladesh: Private provision of local public goods and community regulation,” Paper Presented in Workshop on Managing Common Resources at the Department of Sociology, Lund University, Sweden, 2001.

[12] M.A.S Mandal Ed "Dynamics of Irrigation Market in Bangladesh, Changing Rural Economy of Bangladesh. Bangladesh Economic Association, Dhaka, 2000.

[13] Fifth Five Year Plan "Mid- term review of the Fifth Five Year Plan 1997-2002", Planning Commission, Ministry of Planning, Government of Bangladesh, Dhaka, Bangladesh, 2000.

[14] S. Islam and A.N M.R Karim Ed, "Increasing Rice Production in Bangladesh: Challenges and Strategies" International Rice research Institute, Los Banos, 1999

[15] M. K. Mondal, T.P Tuong, S.P Ritu, M.H.K Chowdhury, A. M Chasi, P.K Majumder, M.M Islam and S.K Adhikary " Coastal water resource use for higher productivity; Participatory research for increasing cropping intersity in Bangladesh" Paper presented in the international conference on Environmental and livelihoods in the coastal zones; managing agriculture- aquaculture conflicks held in Bac Lieu, Vietnam, March 2005.

[16] NWPo. (1999). National Water Policy, Ministry of Water Resources, Dhaka, Bangladesh, 1999.

[17] Stephan K, R. Kipfer, Olaf A. C, Charles F. Harvey, M S. Brennwald, K. N. Ashfaque, A B M. Badruzzaman, S J. Hug, and Dieter M. **(**2006) Groundwater Dynamics and Arsenic Mobilization in Bangladesh Assessed Using Noble Gases and Tritium, Environmental Science and Technology,.(http://pubs.acs.org/doi/abs/10.1021/es0512 4w)

[18] M. A Sattar, and M. Moniruzzaman "Innovative Rice-based Farming Practices for Increasing Food Security in the Changing Coastal Environment of Bangladesh', in proceedings BKAS 13th National conference and seminar on Climate Changes: Food Security in Bangladesh, Vol. 13, Dhaka, Bangladesh, August 2008.

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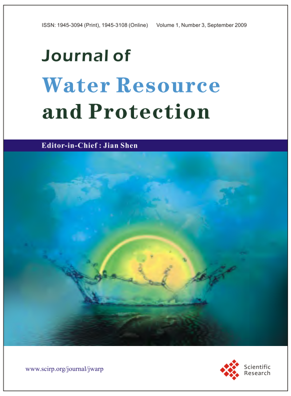

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