Study of Point of Use Treatment Methods for the Disinfection of Drinking Water in Nepal

by

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ABSTRACT

The Kathmandu Valley of Nepal is a densely populated region, faced with a chronic unavailability of safe drinking water. Due to the incomplete reach and intermittent supply of municipally supplied tap water, many residents of the Kathmandu Valley are forced to use water from alternate sources such as surface water from streams and rivers and ground water from springs and wells. All three sources of water, municipal tap water, surface water and ground water are severely polluted.

This study explores point-of-use disinfection as a means of allowing consumers to treat their own drinking water on a household scale.

Three disinfection options, chlorine, ultraviolet, and solar were tested in the course of this study. Laboratory testing was complemented by field tests conducted in January 2000 in the Kathmandu Valley in order to determine the *in-situ* viability and functionality of each method.

Ultraviolet disinfection proved infeasible due to unreliable electric power supplies and the high cost of the units. Chlorine, though performing well in the laboratory, had a major drawback of not being available in retail outlets in the Kathmandu Valley. Solar disinfection was tested using locally available transparent plastic and glass containers. Solar, microbial removal was inconsistent in laboratory tests. Solar disinfection is in need of further study in the local context of Nepal.

Chlorine disinfection proved to be the most reliable point-of-use treatment option, when available. Though highly dependant on regional and seasonal variations in solar radiation availability, solar disinfection, may offer an attractive complement or alternative to chlorine disinfection. Extensive, region specific solar radiation data are needed prior to the recommendation of a solar disinfection regime in Nepal.

Thesis Supervisors: Susan Murcott and E. Eric Adams
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DEDICATED TO MY PARENTS FADIA AND 'ADNAN
TO WHOM I OWE EVERYTHING

TO MY SIBLINGS MUNIRA, GHASSAN, YASMINE AND ROLA
FOR HELPING KEEP SANITY AT BAY

AND TO MY BELOVED KATTY SHAFIEE

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OVERVIEW OF DRINKING WATER IN NEPAL

1 Sources of drinking water in the Kathmandu Valley and environs

1.1 Introduction

Nepal is a sovereign kingdom that lies between the People's Republic of China and the Republic of India. Straddling the transition between the lowlands of the Indo-gangetic plain and the highlands of the Himalayan mountain range, Nepal is a country of striking geographic contrasts. These geographic contrasts are reflected in the state of water supply in this mountainous nation. Although Nepal has abundant freshwater resources, their accessibility for human consumption varies greatly. Out of the total population of Nepal, only 34 percent have access to safe drinking water (Adhikari, 1998).

Surface water in the Kathmandu Valley is severely polluted by industrial effluents, waste dumping, and by the discharge of untreated sewage from residential areas. Runaway pollution has rendered the water quality of the rivers of the Kathmandu Valley, the Bagmati, Vishnumati, Manohara and Hanumante comparable to that of raw sewage (Adhikari, 1998; Wolfe, 2000). The ground water in most of the urban areas is also contaminated due to seepage from improperly designed private septic tanks[1].

[1] Private septic tanks built without sufficient room for soak pits are common in the Kathmandu area due to the limited reach of the municipal sewer system.for more information see (Bittner, 2000)

1.2 Traditional water sources, public and private wells

Piped water supplies are still not available to the majority of Nepalese (see Table 1-1). More than one-third drink water from tube wells or hand-dug wells and the rest utilize stone taps, open wells, open reservoirs and streams as sources of drinking water (UNDP HDR, 1998).

Stone water spouts are the traditional source of drinking water in the towns of the Kathmandu Valley. These flowing spouts are located within rectilinear pits built into the ground. The spouts are supplied water through *Raj Kulos* (state canals), an ancient network of canals that connect to local water sources.

Tube wells are fairly common in the Kathmandu Valley, either as hand-pump operated public water sources or on the private property of the wealthier elements of society.

Distribution of households in Nepal by source of drinking water and rural/urban location, 1991 and 1996 (percent)

	1991		1996	
Sources of drinking water	Rural	Urban	Rural	Urban
Piped water	16.3	51.3	29.1	57.4
Well water	12.1	6.4	7.0	8.7
Hand pump	26.5	38.6	33.3	27.3
Spring water (*kuwa*)	32.9	2.9	20.8	0.0
River/stream	9.09	0.2	7.6	3.3
Stone tap	2.7	0.6	1.6	1.8
Others	0.6,	0.1	1.4	0.6
Not stated	0	0	0.3	0.9

Table 1-1: Distribution of households in Nepal by source of drinking water and rural/urban location, 1991 and 1996 in percent (Source: UNDP HDR, 1998)

1.3 Municipally supplied piped water

Modern intervention for improving drinking water in Nepal started in the Kathmandu Valley more than one hundred years ago (Moench *et al*, 1999). A century later the national water supply network is far from complete. In urban areas such as Kathmandu, access to piped water is available to some 58 % of households (UNDP HDR, 1998), and to a mere 31 % of the peri-urban households.

Furthermore, even in areas in which water is more accessible and/or is piped to the settlement or to the house, the safety of the water for human consumption is questionable. This is particularly true in the urban areas where the health workers, the Department of Water Supply and Sewerage (DWSS) and the mass media regularly counsel residents to drink only boiled water. In urban areas, *E. coli* counts in drinking water are reported to be high and increasing (UNDP HDR, 1998).

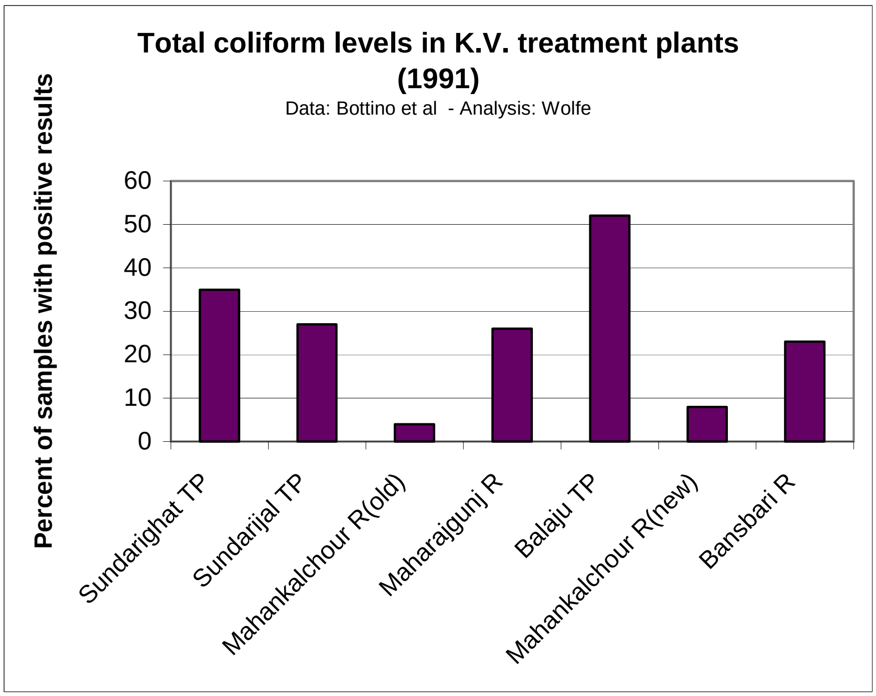

Figure 1-1: Total coliform levels in the Kathmandu Valley Treatment Plants (Source: Bottino *et al*, 1991, Analysis: Wolfe, 2000)

Bacterial contamination of piped drinking water in the Kathmandu Valley occurs at all four of the major junctures in the treatment and distribution process, the source, the treatment plant, the distribution system and the final consumption point i.e. "between tap and mouth".

Municipal water output is not only of uncertain microbial safety, it is also intermittent. During periods when piped water is not being supplied, a negative pressure is formed in the distribution pipes. This negative pressure allows contaminated groundwater and possible leakage from the sewer system to be drawn into the water supply pipes, further contaminating the drinking water (Rijal *et al*, 1998).

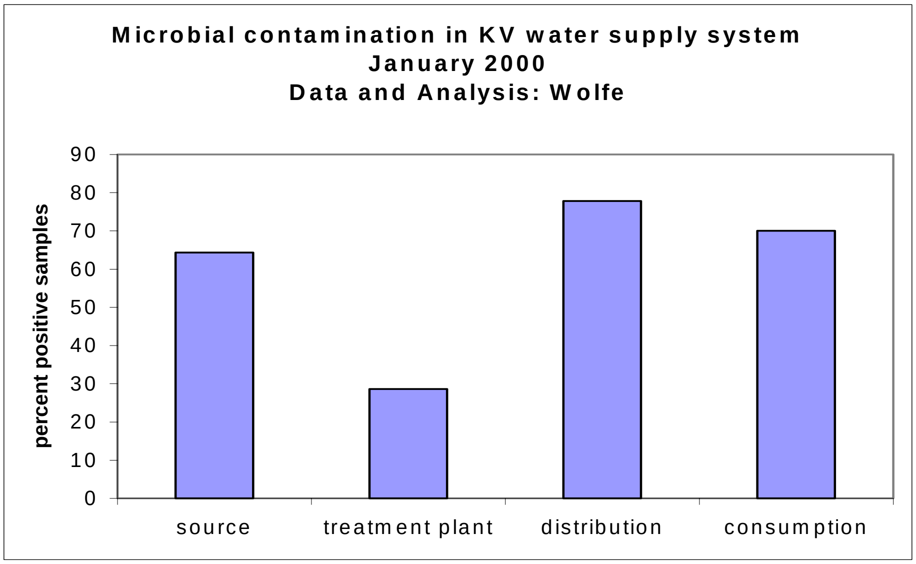

Figure 1-2: Microbial Contamination in the Kathmandu Valley (KV) Water supply system-January 2000 (Source: Wolfe, 2000)

Empirical studies of drinking water throughout Nepal have found that fecal coliform contamination in the water consistently exceeds World Health Organization guidelines for water considered fit for human consumption (Bottino *et al*, 1991*;* Shrestha RR *et al*, 1992*;* Karmacharya *et al*, 1995).

Seasonal variation in water quality is a complicating factor in the task of assuring safe drinking water. The seasonal variation is particularly severe due to Nepal's monsoon climate, which is characterized by great variability in precipitation levels from season to season[2]. Annual precipitation is between 1,800mm and 1,900 mm in the eastern Terai and between 760mm and 890 mm in western Nepal. Flooding is a serious problem in the low-lying areas of the Terai plain during the monsoon season (July-mid-October). Even where flooding is not a problem, the increased amounts of run off, due to the heavy rain results in a deterioration in the available water quality, both in the sources and in the distribution systems (see Figures 1-3, 1-4 below).

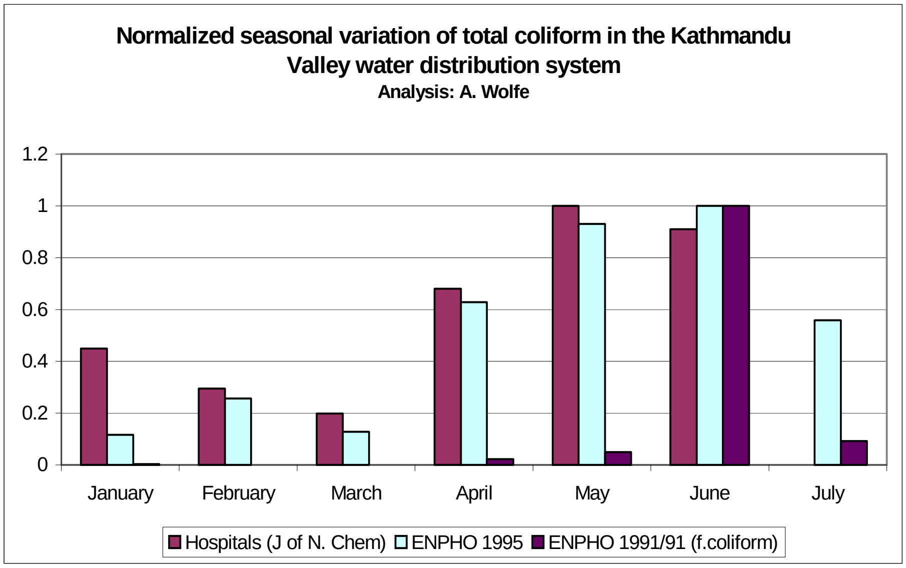

Figure 1-3: Seasonal Variation in total coliform levels in the Kathmandu Valley water distribution system (Source: Bottino *et al*, 1991; Karmacharya, 1992; Shrestha RR., 1995. Analysis: Wolfe, 2000)

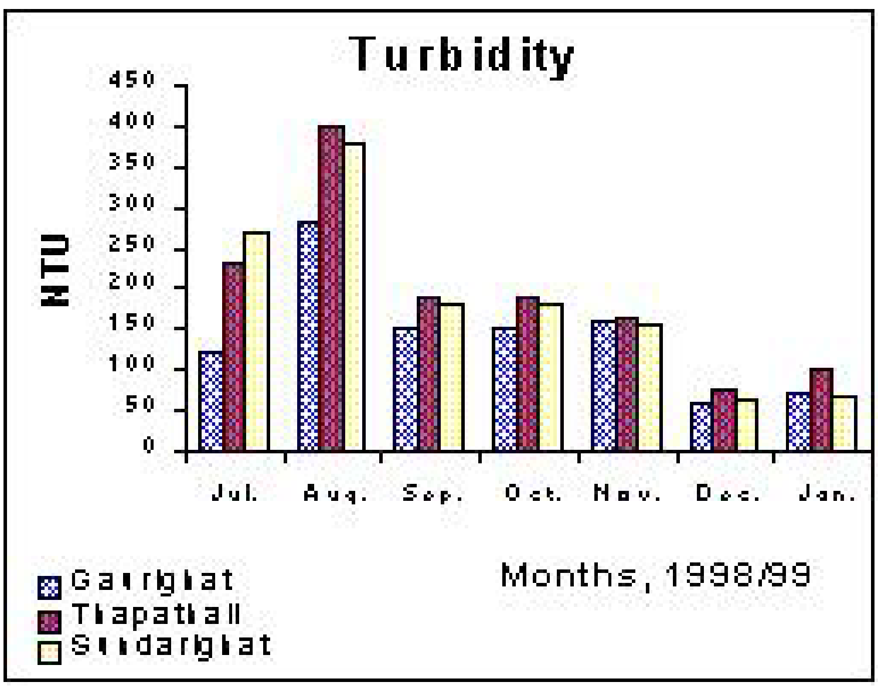

Figure 1-4: Seasonal Variation in turbidity of the Baghmati River measured at three different sampling points (Source: NESS, 1999)

[2] The climates of the Terai and the Kathmandu Valley are characterized as subtropical and temperate monsoon climates respectively (Nepal Ministry of Home Affairs).

2 MICROBIAL SAFETY OF WATER IN KATHMANDU VALLEY AND ENVIRONS

2.1 Types of Contamination

Perhaps the most important indicator of microbial contamination of drinking water is the incidence of gastrointestinal disease. Virtually every gastrointestinal ailment conceivable is present and prevalent in Nepal. Typhoid, gastroenteritis, hepatitis and cholera are all pandemic in Nepal, afflicting a large portion of the society (Bottino *et al*, 1991).

2.2 Sources of Contamination

Drinking water contamination in the Kathmandu Valley is primarily from human and animal sources. The valley is marked by an absence of functional sewage treatment plants, which has contributed to the high incidence of waterborne disease (Rijal *et al,* 1998). The sewerage system generally transports human sanitary wastes to one of the rivers of the valley to be dumped untreated into the surface waters. In areas not serviced by sewers, sanitary waste is either deposited into septic tanks, which frequently leach into the ground water, dumped directly into surface water or are simply left in open spaces.

2.3 Ramifications of contamination on public health

In Nepal the assurance of public health, sanitary facilities and safe drinking water are inextricably bound issues. In the numerous communities without adequate sanitation, pathogen-laden human and animal wastes, food, and garbage pile up near homes, or drain into waterways to infect drinking water supplies. The implications of this contamination are severe since inadequate health care infrastructure in Nepal, means illness often results in death (Adhikari, 1998; UNDP HDR, 1998). According to the National Family and Fertility Health Survey (NFFHS), the infant mortality rate was 79 per 1000 births and the mortality rate for children under 5 years of age was 118 per 1000. The Nepal Ministry of Health estimates released in 1998/9 indicate that 80,000 children under 5 die annually from preventable diseases (Acute respiratory infection, diarrhea, measles, neonatal tetanus, whooping cough and diphtheria). Hardly any reduction has taken place in the last 10 years, indicating that sanitation and hygiene as well as water quality have not improved (personal communication, Hans Spruijt UNICEF-Nepal).

Distribution of households in Nepal with private latrines, 1991 and 1996 (in percent)

	1991		1996	
Toilet in the house	Rural	Urban	Rural	Urban
Yes	16.5	69.8	17.7	73.7
No	83.5	30.2	82.3	26.3

Table 2-1: Distribution of households in Nepal with private latrines, 1991 and 1996 (Data source UNDP HDR, 1998)

SECTION II

POINT-OF-USE DISINFECTION

3 POINT-OF-USE (POU) DISINFECTION – LITERATURE REVIEW

3.1 Introduction

Large-scale water treatment ventures in the developing world have often been costly failures (Moench *et al,* 1999). This has led to a growing awareness that water treatment processes considered reliable and adequate in developed countries such as coagulation, filtration and chlorination are often beyond the capacity of local skill and resources. There has been a recent resurgence of research into small-scale alternatives for water treatment that would be both more affordable to and more viable in underdeveloped regions.

In the past fifty years Nepal has experienced an unprecedented population increase (UNDP HDR, 1998). This population increase has also been accompanied by a rapid urbanization of the populace, with many inhabitants of the rural regions moving to the cities, in search of employment and betterment. The rural influx into Kathmandu and the cities of the Terai has stretched their already limited water supply and sanitation infrastructure to the breaking point. The sanitary decline associated with population increase has also rendered many of the traditional water sources unfit for human consumption. With neither municipal nor traditional sources able to supply the urban population with safe water, the need for alternative water treatment methods becomes clear. Point-of-use treatment is one such alternative, providing a medium term solution to the shortage of safe drinking water.

In most texts not dedicated to development work, POU treatment is usually dealt with as a stop-gap measure in case of a catastrophe. It must be noted however that the recommendations in such documents (e.g. Federal Emergency Management Agency, 1998; and the University of Florida Disaster Handbook Guide, 1993) are guidelines to be followed for the duration of the crisis only. The assumption of the immanent return of safe water is often unquestioned. As such, there is little consideration given to the effects of long-term usage of such methods, as would be necessary in a country of chronic water shortages such as Nepal.

Even texts dedicated to household level treatment systems for long term applications frequently concentrate only on the technical criteria for such devices, without taking into consideration the varied matrix of technology and society in which they are to operate. Following is one such list of design and safety criteria from a conventional textbook on household water treatment (Lehr *et al*, 1980).

1. The disinfectant should be effective on many types of pathogens and on whatever numbers may be present in water
2. The disinfectant should perform properly regardless of water flow fluctuations
3. The temperature and pH range in which the disinfectant will be required to operate must be adequate.
4. The disinfectant must not make the water either toxic or unpalatable
5. The disinfectant must be safe and easy to handle
6. The concentration of the disinfectant (if chemical) must be minor
7. The disinfectant must provide residual protection against possible recontamination

(Adapted from Lehr *et al*, 1980)

For a disinfection method to be adaptable to point-of-use application in an underdeveloped part of the world, the above criteria are necessary but far from sufficient. Additional factors to be considered include those listed below along with many others that are dependent on the vagaries of the local surroundings:

1. Cost; the units must be affordable to all, especially those in the lower income brackets, the ones least likely to have access to treated water.
2. Adaptability to local conditions, regional variations in water usage patterns and water quality must be considered.
3. Utilization of specialized equipment in the treatment process should be limited to that produced locally.
4. Indigenous materials and manufacture should be used to reduce costs and bolster the local economy.
5. Influence of local traditions, customs and cultural standards.
6. Influence of national sanitation and pollution policies.

(Adapted from Shultz *et al*, 1984)

For this study, three methods will be analyzed, ultraviolet disinfection (UV), chlorination and solar disinfection. A literature review of these three methods will give a preliminary assessment of compliance with the stated POU application criteria. The final assessment of compliance is the result of field tests conducted during January 2000 AD and which will be elaborated in the coming chapters.

The discrepancy in the composition and length of the following chapters is a reflection of the relative standing each one of these disinfection methods has in the eyes of the scientific community. Chlorination and to a lesser extent, ultraviolet disinfection, are conventionally accepted and exhaustively studied and documented methods of disinfection. The sections devoted to chlorination and UV disinfection are intentionally brief, and consist of a basic overview of the properties of the technique and its potential for application as a POU treatment method. Solar disinfection, on the other hand, is a relatively novel approach and for this reason, there is a scarcity of research and information sources. The section on solar disinfection is considerably longer and more elaborate than that on the other two disinfection methods, as there is much groundwork to cover.

3.2 Chlorine Disinfection

The use of chlorine and its compounds is indisputably the most common method for disinfection of water in use today (Water Review, 1996). Due to chlorine's popularity, there exists an exhaustive amount of literature on its application.

Chlorine's popularity stems from three main criteria: it is relatively inexpensive, it has a proven effectiveness, and a simple test exists to measure its performance.

Chlorination is typically performed utilizing one of three different chemical compounds of the chlorine molecule, gaseous elemental chlorine (Cl_2), solid calcium hypochlorite ($Ca(OCl)_2$) or liquid sodium hypochlorite ($NaOCl$).

Elemental chlorine is a toxic, yellow-green gas that becomes liquid at high pressures. Chlorine gas is often used in water treatment plant chlorination as it is very effective for removing almost all microbial pathogens and is appropriate as both a primary and a secondary disinfectant. The applicability of elemental chlorine in a POU system on a household level is inappropriate, as it is a dangerous gas that is lethal at concentrations as low as 0.1% air by volume.

Sodium hypochlorite solution, or liquid bleach, is available as a solution in concentrations of 5 percent to 15 percent chlorine. In many parts of the world, sodium hypochlorite is used for bleaching and cleaning purposes and is readily available. It is also used extensively for water disinfection, but as it is more expensive than gas as available chlorine, and therefore may not be the most economical solution. Liquid bleach has the advantage of being easier to handle than gas or calcium hypochlorite but is limited by its corrosivity and lack of stability. It is also relatively easy to produce. Using specialized equipment, liquid bleach can be generated onsite, requiring supplies of common salt and electricity (Water Rev., 1996). Liquid bleach lends itself well to POU application, due to its availability and relative manageability.

Calcium hypochlorite, a primary component of bleaching powder, is a white solid that contains up to 65% available chlorine and dissolves easily in water. When packaged, calcium hypochlorite is very stable, and can be stored for up to a year. However it is very corrosive and odiferous and requires proper handling since reactions between it and organic material can generate enough heat to cause a fire or explosion. It readily absorbs moisture forming chlorine gas; thus shipping containers must be emptied completely or carefully resealed. Calcium hypochlorite may be purchased in granular, powdered or tablet form however it is several times more costly than sodium hypochlorite solutions (Culp *et al,* 1974). Cost aside, calcium hypochlorite is also amenable to adaptation to POU application. There are a number of companies that sell chlorine tablets (with $Ca(OCl)_2$ as the active ingredient) for the use of campers and in emergency situations.

3.2.1 Chemical Processes

Upon the addition of chlorine to water, it first combines with inorganic compounds (hydrogen sulfide, ferrous iron, and manganese) in what is termed the inorganic chlorine demand; there is no disinfection at this stage. After these compounds have been reduced, the remaining chlorine reacts with organic matter (algae, phenols, and slime growth) satisfying the organic chlorine demand. While some bad tastes and odors may be eliminated, there is only a slight disinfection action at this stage. After the demand exerted by inorganic and organic compounds has been met, chlorine will combine with nitrogen compounds (primarily ammonia) to form chloramines. This combined chlorine form is a slow-acting, yet long-lasting disinfectant. It produces minimal chlorine taste and odor and controls organic growths; however, the contact times required to achieve disinfection at this point are prohibitively long. When even more chlorine is added to the water, the chloramines are destroyed and a free residual is produced in the form of hypochlorous acid (HOCL).

$$XCl_X + H_2O \leftrightarrow HOCl + H^+ + Y$$

Hydrolysis goes virtually to completion at pH values and concentrations normally experienced in water treatment

$$HOCl \leftrightarrow H^+ + OCl^-$$ [3]

[3] The disassociation rate from hypochlorous acid to hypochlorite is sufficiently rapid so that equilibrium is maintained even though the former is being continually consumed.

HOCL is a potent, fast reacting disinfectant. The short contact times for total disinfection make it the most tractable form to use in a disinfection process. The amount of chlorine dose required to create sufficient quantities of HOCL depends on a number of factors that are listed below:

1. Bacterial Numbers: Large numbers of aerobic or anaerobic bacteria in the water require a high chlorine dosage to ensure that all disease causing organisms have been destroyed.
2. pH: Hypochlorous acid (HOCL) will form in waters ranging from pH 6.5-7.5. As the pH increases above 7.5, HOCL increasingly disassociates to the hypochlorite ion, which is 250 times less effective as a disinfectant than HOCL. Under pH of 6.5, HOCL is reduced and HCL, a very weak disinfectant is formed (Viessman and Hammer, 1996)[4].
3. Temperature: Speed of disinfection is positively correlated with increasing temperatures.
4. Turbidity: Effective microorganism destruction will only begin after the chlorine demand exerted by turbidity (inorganic and organic compounds) is met. In addition, chlorine is a surface-active agent and since it can not effectively penetrate solids to kill concealed bacteria, disinfection of turbid water can be incomplete.

3.2.2 Limitations of Chlorine Disinfection

In spite of its worldwide popularity as the treatment method of choice in centralized large-scale water distribution treatment plants and networks, chlorination has a number of drawbacks that may affect its applicability to a POU treatment system. Objections to chlorination have arisen due to aesthetic, logistic and health-related concerns.

On the aesthetic level, chlorination frequently leads to consumer complaints and rejection because of the undesirable tastes and odors imparted to the water. While developed countries may have the educational capabilities to teach lay people of the benefits of

[4] Generally HCl doesn't become a problem in the desired pH range of drinking water.

chlorination, this may be a significantly harder task in lesser-developed countries (LDCs) that lack this ability.

The procurement/manufacturing, distribution, accurate handing and dosing of chlorine can be the cause of numerous limitations on its applicability in a household context.

The health hazards of chlorine are not limited to its corrosive and volatile nature. There is concern over the toxicity of chlorine byproducts and incompletely oxidized compounds that are quite frequently present in chlorinated water. Chloro-organics and trihalomethane (THMs) are the most notorious byproducts of chlorination[5]. THMs are formed when chlorine reacts with humic and fulvic acids present in the water due to contamination of the source water with organic material. Studies have identified some of these chloro-organics as potential carcinogens, mutagens or toxins (Viessman and Hammer, 1996). One THM in particular, chloroform, is a documented animal carcinogen. The United States Environmental Protection Agency (USEPA) has set guidelines that THMs are not to exceed 0.10 milligrams per liter. THMs are of particular concern in a POU treatment system as the water being treated is likely to have a high organic content and not have had the benefits of pretreatment. This would lead to high concentrations of THMs, which may lead to health complications

3.3 Ultraviolet Disinfection

A growing trend in drinking water disinfection is the use of UV disinfection units. The design of the UV units is quite simple, consisting of a UV light source enclosed in a transparent protective sleeve. The light source is mounted so that water can pass through a flow chamber, and UV rays are admitted and absorbed into the stream. An advantage of this method is that it does not change the taste or odor of the water being treated. Contact time is also very short as the UV rays kill bacteria almost immediately. (Lehr *et al,* 1980)

[5] An extensive study on the occurrence of disinfection byproducts in 35 water treatment plants processing surface waters indicated that THMs accounted for about 50% of the total by-products on a weight basis (Viessman and Hammer, 1996).

3.3.1 Physical Process

Light is commonly divided into regions or bands on the basis of wavelength.

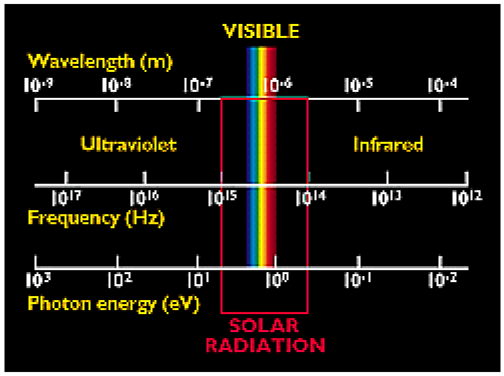

Figure 3-1: The spectral breakdown of solar radiation (source)

The UV wavelengths lie between 100 and 400 nm. UV light is in turn divided into four major components, Vacuum UV (extreme UV), UV-C (Far UV, germicidal radiation), UV-B (Mid UV, sunburn or erythmal radiation) and UV-A (Near UV, blacklight).

UV radiation at the wavelength of 254nm (UV-C) is a potent germicide, which can be used to disinfect drinking water. The germicidal effect of UV-C is directly related to the induction of changes in nucleic acids, primarily through the formation of thymine-dimers (Wegelin *et al*, 1994). Excessive radiation with UV-C can additionally lead to conformational changes of essential structures, such as enzymes and immunogenic antigens. UV treatment is effective on most pathogens found in water, but a hierarchy of resistances exists. Free floating bacteria are most susceptible followed by viruses, bacterial spores, and amoebic cysts that require 3-4 times, 9 times, and 15 times higher doses respectively to achieve equivalent levels of disinfection (Wegelin *et al*, 1994).

Experiments using microbial suspensions in buffered sterile water exposed to UV-B radiation have been conducted in order to determine the resistance of some microorganisms. These have been ranked as follows

A.castellanii cysts > *Bacillus subtilis* spores > simian *rotavirus* > standard plate count > *S. Faecalis* > total coliforms > *E. Coli* > *Streptococcus aureus* > *Shigella sonei* > *S. Typhi* (Acra *et al*, 1990).

3.3.2 Limitations of Ultraviolet Disinfection

UV disinfection has several limitations with respect to POU application in underdeveloped areas. The primary limitation of this technique is its energy requirement. In many LDCs electric power availability cannot be guaranteed. Though the efficacy of this method is impressive under controlled conditions, there exists no simple test to determine whether the system is providing proper disinfection in the field. Additionally UV disinfection does not leave a residual, making it only effective as a primary disinfectant. It does not serve as a second barrier, i.e. it does not guard against reinfection of the water after treatment.

The chemical composition and microbial quality of the influent water is also of critical importance to UV disinfection. Microbial quality is of concern because bacteria could be shielded in cloudy or turbid water or in water that is contaminated by large numbers of bacteria[6]. Chemical composition is relevant since water containing high mineral levels may cause a coating on the lamp sleeve, reducing the effectiveness of the treatment. Water softeners or phosphate injectors may be needed to prevent coating of the lamp. UV devices are thus most effective on partially treated water or water of naturally low turbidity, which may not be available in the field.

3.4 Solar Disinfection

Overlooked by Western science, the technique of solar water disinfection has been used for centuries in various parts of the world (Acra *et al*, 1990).

The basic premise of this technique is to use solar energy in the form of infrared heat and ultraviolet radiation to disinfect water. Water to be treated is exposed to the sun in

[6] An upper limit of the use of UV for disinfection is 1000 total coliforms/100 ml or 100 fecal coliforms/100 ml (Mancl, 1989).

transparent containers for a certain amount of time and solar radiation in the form of UV-A disinfects pathogenic microorganisms. Several studies in various parts of the world have reported success in removal of pathogenic organisms from drinking water. This technique is highly dependent on the availability and quality of solar energy and the clarity of the water being treated. Determining the efficacy of this technique in a regional context requires extensive field tests.

Research into the field of solar water disinfection was initiated by a group of scientists at the American University of Beirut in the late 1970s (Acra *et al*, 1984). In these studies, disinfection was conducted using batches of transparent containers. The containers used were clear or blue tinted containers made of glass or plastic. The stated results confirmed the effectiveness and feasibility of the solar decontamination of water in small quantities (<3 L). The data gathered from these tests are further elaborated below.

Based on this pioneering work in the early 1980's, the Integrated Rural Energy Systems Association (INRESA), an associated program of the United Nations University, supported several other research projects on solar water disinfection. Preliminary findings supported those of the researchers in the American University of Beirut; ground and surface water infected with many kinds of bacterial pathogens can be made safe to drink through solar disinfection.

Further studies and field trials in numerous countries have been conducted by the Swiss Federal Institute for Environmental Science and Technology (SANDEC/EAWAG). In 1991 SANDEC embarked on an extensive laboratory and field test project in order to assess the potential of solar water disinfection and develop further what they believed to be a sustainable and low-cost method for treatment of small quantities of drinking water at the household level (B.Sommer *et al,* 1997). The demonstration projects were carried out by local institutions in seven countries to study the socio-cultural acceptance and affordability of this treatment option. The SANDEC project has been subdivided into three phases:

1. Comprehensive laboratory and field tests to determine the potential and limitation of the process
2. Field tests to develop equipment and operating guidelines for the water treatment method
3. Demonstration projects to study socio-cultural acceptance and affordability of Solar Disinfection

Countries in which field tests are being conducted are: Colombia, Bolivia, Burkina Faso, Togo, Indonesia, Thailand and China. The selected sites comprise a large range of different socio-cultural backgrounds as well as climactic and living conditions (EAWAG/SANDEC, 1997).

SANDEC/EAWAG is presently working on scaling up the implementation of this technique from the small-scale grass root non-governmental organization (NGO) level where it has been adopted with considerable enthusiasm, to the national and international development organization level where it is still treated with an element of doubt.

There have been numerous other independent research efforts in both the field and the laboratory (Conroy *et al,* 1996; Reed *et al,* 1997; McGuigan *et al,* 1998), however this technique is still in the testing phase and remains unknown in many parts of the world.

3.4.1 Optical inactivation of Bacteria and Viruses

There is consensus in the literature that UV-A light (320-400nm) is the component of sunlight primarily responsible for the inactivation of microorganisms (Acra *et al,* 1984; Acra *et al,* 1990; Conroy *et al,* 1996; Joyce *et al,* 1992; Reed, 1997; McGuigan *et al,* 1998). The inactivation mechanism involves the absorption of the light by photosensitizers that become electronically excited and react with neighboring oxygen molecules leading to the production of highly reactive oxygen species that cause strand breakage and base changes in DNA. Strand breakage is usually lethal while base changes may result in a block in replication and other mutagenic effects (McGuigan *et al,* 1999).

Studies on solar inactivation of bacteria have focused on *E. Coli, S. Faecalis* and total coliform. Studies have shown that the responses of these bacteria are likely to be representative of a broader range of fecal bacteria including enteric pathogens (Acra *et al*, 1990).

There is some divergence in the literature with respect to the inactivation rates of these bacteria. Some studies (Wegelin *et al*, 1994; Reed, 1997) have suggested that the inactivation rates are equivalent. While others have indicated that *S. Faecalis* required relatively more solar UV-A fluence for inactivation than *E. Coli* (Acra *et al*, 1990). Numerous explanations for this divergence have been proffered such as differences in strain history and/or experimental conditions (Wegelin *et al*, 1994). Recent research has also indicated that solar disinfection will only be effective under fully aerobic conditions (Reed, 1997), which may provide an additional explanation for the variable results of many of the studies which frequently did not take oxygen content into consideration.

The data available on viral inactivation is not complete. Of the viruses studied so far (*Bovine rotavirus, encephalomyocarditis virus, bacteriophage fs* and *polio virus*) appear quite sensitive to solar disinfection (Wegelin *et al*, 1994). It is suggested that this may be due to viral inability to repair optically damaged DNA (McGuigan *et al*, 1999).

3.4.2 Thermal inactivation

Although no significant correlation has been observed between mean water temperature values and percentage bacterial survival in the range of 5 ^{o}C to 37^{o}C, thermal inactivation remains an important part of the solar disinfection process. This is due to strong evidence of a synergetic heat effect on solar disinfection when water temperatures above 45^{o}C are achieved (Wegelin *et al*, 1994, McGuigan *et al*, 1998).

Studies have shown *E. Coli* and *S. Faecalis* inactivation occurring at least three times faster at 50 ^{o}C than in the 20 ^{o}C - 40^{o}C range[7] (B.Sommers *et al,* 1997; Wegelin *et al,* 1994). In fact, thermal pasteurization is the primary bacteriocide at temperatures exceeding 65^{o}C (Andreatta *et al*, 1994; McGuigan *et al*, 1998). Although it has proven to be difficult to heat water to 65^{o}C using the batch type solar disinfection technique studied in this paper (Acra *et al,* 1984; Wegelin *et al*, 1994; Conroy *et al*, 1996), temperatures around 45^{o}C are common.

Viral inactivation appears to have a similar boost upon temperature increase, with one study indicating an increase in inactivation rates when water temperature was raised from 20 to 40^{o}C (Wegelin *et al*, 1994).

3.4.3 Solar Radiation

Solar radiation is partially depleted and attenuated as it traverses the atmospheric layers, preventing a substantial portion of it from reaching the earth's surface. This phenomenon is due to absorption, scattering and reflection, which occur mainly in the stratosphere and troposphere.

The stratospheric ozone layer has a strong, wavelength dependant, absorption affinity for solar UV radiation. Ozone layer UV absorption is more effective at the shorter wavelengths. It reaches a peak at 250nm and drops off rapidly above 350nm. The ozone layer thus has the effect of shielding the earth from harmful radiation of wavelengths below 280 nm, vacuum UV and UV-C, allowing only a fraction of the UV-B and UV-A wavelengths reach ground level (Iqbal, 1984).

The troposphere is an attenuating medium. Solar radiation is reflected and refracted by clouds, particulates and various gases. Two scattering processes are selective scattering and non-selective scattering.

[7] As with most disinfection techniques, the synergetic heat effect seems dependent on microorganism type, with strains such as Entercoccus not showing as strong a temperature effect as the other type listed above

Selective scattering is caused by particles that are the same size or smaller than the wavelength. Scattering in these cases is inversely proportional to wavelength and is most effective for the shortest wavelengths. The degree of scattering decreases as follows

UV-B > UV-A > Violet > Yellow > Orange > Red > Infrared

When the atmosphere is clear and relatively transparent, selective scattering is less severe than when it is extensively polluted. Selective scattering may range from 10% in the early morning to 20% in the late afternoon (Acra *et al*, 1990).

Nonselective scattering is caused by dust, fog, and clouds, with particle sizes more than ten times the wavelength of the incident radiation (Iqbal, 1984). As scattering in this case is not wavelength dependant, it is equal for all wavelengths, causing a general diminishment of incident radiation across the spectrum.

In general, the ultraviolet radiation component does not exceed 5% of the total incident radiation at sea level under cloudless conditions (Iqbal, 1984). However it is important to note that the intensity of sunlight at ground level is dependant on a host of variables including but not limited to, latitude, geographic location, season, cloud coverage, atmospheric pollution, elevation above sea level and solar altitude.

At high altitudes, the intensity of ultraviolet radiation is significantly higher than at sea level[8]. The altitude effect on broadband UV-A radiation ranges from 9% to 24% per 1000 meters (Blumthaler *et al*, 1993). Due to the scattering effects described above, polluted atmosphere over large cities robs solar radiation of a significant portion of its ultraviolet light.

[8] An important point for the case of Nepal

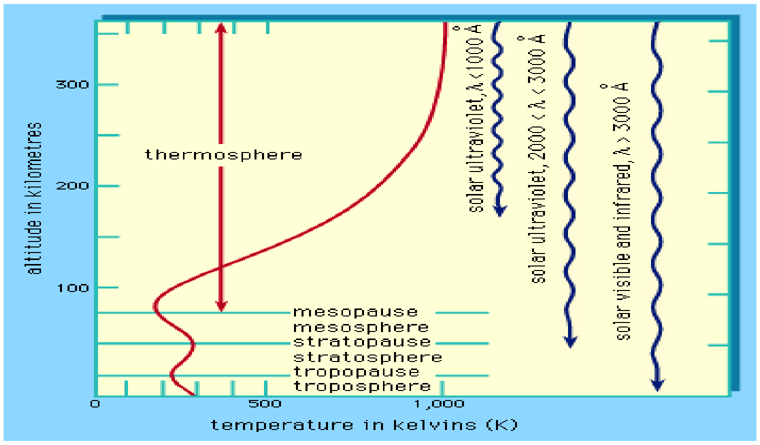

Figure 3-2: Atmospheric penetration of solar radiation according to wavelength (Encyclopædia Britannica Online)

3.4.4 Transmission of sunlight through various media

In order to maximize the disinfectant efficacy of the incident sunlight it is essential to minimize the transmission losses through the water container. Solar energy impinging upon a transparent medium or target is partly reflected and partly absorbed; the remainder is transmitted. The relative values are dependent on the wavelength of the incident light and the optical properties of the container.

Transmission of the incident solar energy through glass is a function of the type and thickness of the glass, the angle of incidence and the specific wavelength bands of radiation. Ordinary glass of the soda-lime-silica type (window or plate glass) is opaque to UV-B, but transmits more than 90% of incident UV-A and visible light. Increasing the thickness and iron content of the glass diminishes transmittance. The transmittance is uniform at a high angle ranging from 0 to 40 degrees and drops sharply as the angle approaches 90 % (Acra *et al,* 1990). Transparent plastic materials such as Lucite, Plexiglas, Polyvinylchloride (PVC) and Polyethyleneterephtalate (PET) are also good transmitters in the UV and visible ranges of the spectrum (Acra *et al,* 1990).

The transmittance of the raw water is also of importance since solar radiation passing through water is attenuated by reflection and absorption. The transmittance of water is dependant on water depth, turbidity and the optical properties of the water. Increasing turbidities leads to increased attenuation of transmitted light. Turbidities above 200NTU can absorb as much as 99% of the incident radiation within the first centimeter of optical path[9] (Joyce *et al,* 1996). It is expected that optical inactivation will be significantly retarded in such conditions. A number of papers have suggested however that the thermal inactivation process may be aided due to the increased thermal inertia of the darker surface (McGuigan *et al,* 1998; Reed, 1997).

3.4.5 Limitations of Solar Disinfection

The research effort on solar water disinfection is far from comprehensive and well-documented field trials are rare. There have been no reports on the efficacy of this method on critical water borne pathogens such as Norwalk virus, hepatitis A, hepatitis E, protozoa, helminthes or cysts of *G. lamblia, G. muris* and *E. histoylica*[10] (McGuigan, 1999).

Even barring the need for further research, the application of solar water disinfection is limited by certain crucial factors that may render it inappropriate or insufficient as a POU disinfection method. The main and perhaps most obvious issue is that of climactic conditions. To ensure adequate disinfection, available solar radiation and ambient temperatures must not fall below $500W/m^2$ and 20^oC respectively. As with ultraviolet disinfection solar disinfection requires that the raw water be pretreated or be of naturally low turbidity in order to be effective.

There has been some concern with respect to the leaching of chemicals from plastic bottles into the drinking water, during the solar disinfection process (McGuigan *et al*, 1999; EAWAG/SANDEC, 1999). Most plastic drink containers are presently made from PET. The compounds that could potentially leach from such bottles are acetaldehyde, terephtalic acid, dimethylterephthalate and ethelyene glycol. Terephthalic acid and dimethylterephthalate are genotoxic but they are insoluble in water and then chances of them leaching into water even during solar disinfection, are minimal. Ethylene glycol is

[9]The commonly recommended turbidity threshold for water undergoing solar disinfection is 30 NTU (Wegelin *et al,* 1994; Sommers *et al,* 1997)

[10] Cyst deactivation will occur if water temperatures over 56 ^oC are achieved and maintained for over ten minutes (Andreatta et al, 1994), unfortunately as stated above these temperatures often difficult to achieve.

more water soluble and thus more likely to leach into water. Comprehensive tests have yet to be conducted, however preliminary studies conducted in Malaysia have failed to detect any of these compounds (McGuigan *et al*, 1999).

4 FIELD VIABILITY STUDY METHODOLOGY

4.1 Introduction

The following field tests of the point-of-use disinfection techniques were conducted in Kathmandu, Nepal in the period between 10th and the 29th of January, 2000 AD. The purpose of these tests was to determine the field viability of the three techniques discussed above in the specific regional context of the Kathmandu Valley.

4.2 General Methodology

The stated intention of this study was to find point-of-use disinfection methods for application on a household level in Nepal. Therefore care was taken to use implements and chemicals that were locally manufactured and/or available to as wide a swath of the populace as possible.

In addition to the field tests, a preliminary attempt was made at garnering public opinion on the various methods at hand. People from various occupations were interviewed and questioned as per their current water usage and treatment patterns. The point-of-use disinfection methods were explained and demonstrated to various groups of people and their reactions and observations were noted.

These interviews were conducted informally and do not stand in lieu of, or preclude, a more thorough socio-cultural acceptance study. They are only intended to give an impressionistic introduction to the possible socio-cultural ramifications of a particular treatment method.

4.3 Microbial Testing

Three indicator organisms were tested during the January 200 field study: total coliform, *E. Coli*, and H_2S producing bacteria. Microbial testing was conducted using the HACH™ Presence/Absence (P/A) test with MUG reagent for *E. Coli* and total coliform and a HACH™ most probable number (MPN) test for the H_2S bacteria.

5 FIELD VIABILITY OF CHLORINE DISINFECTION

5.1 Introduction

The use of chlorine as a disinfectant is not an alien concept in Nepal as all five municipal drinking water treatment plants in the Kathmandu valley are designed to use chlorine as a disinfectant. Bleaching powder is imported from India for this use. POU application appears to be limited, although a number of international and national aid groups have made extensive efforts to popularize its use (Conversation, representatives from ENPHO, UNICEF, and Nepal Water Health (NEWAH)).

The aim of the tests conducted was to determine the adaptability to POU application of the type of chlorine available. The first form was a chlorine stock solution provided courtesy of the Environment and Public Health Organization (ENPHO), a Kathmandu based non-governmental aid agency. The other was calcium hypochlorite bleaching powder obtained from the Sundarighat municipal water treatment plant.

5.2 Methodology

A stock solution of 0.5% chlorine was used to dose bacterially contaminated waters, while monitoring the chlorine residual levels and testing for disinfection efficacy. The

ENPHO supplied chlorine, was already in 0.5% solution form and prepackaged in a plastic drop applicator. The bleaching powder was made up as a 0.5% solution by dilution with distilled water. The bleaching powder stocks at the Sundarighat treatment plant had been stored in an area exposed to the elements for an indeterminate amount of time. This bleaching powder was of uncertain and variable chlorine content. The labeled chlorine content was 5% by weight; the eight samples tested yielded chlorine contents ranging between 2.5 and 4.5 percent. The preparation of a stock solution from this bleaching powder was further hampered by the precipitation of excess lime, which added turbidity to the water. Leaving the solution sealed tightly overnight caused the settling of the precipitate and allowed the clear chlorine stock solution to be decanted and used for dosing.

Raw water samples were obtained either from the tap water (on days in which the water was not chlorinated) or from the source water of the Sundarighat treatment plant. A 30-minute contact period was allowed before microbial tests were conducted.

5.3 Availability

Aside from that which is made available through community service projects run by aid agencies[11] chlorine does not appear to be readily available in Nepalese retail establishments. Sodium hypochlorite solutions are not in common usage in laundry and household cleaning applications. A survey of numerous retail establishments in the greater Kathmandu valley located chlorinated products only in a select number of upscale supermarkets patronized mainly by tourists and other non-Nepalese. Even the municipal treatment plants experienced frequent chlorine shortages (personal communication, Dilli Bajracharya, chief chemist of the Central Laboratory of the Nepal Water Supply Corporation (NWSC)).

[11] The stock solution provided by ENPHO is only made available during the monsoon season. It is prepared using bleaching powder supplied by the Kathmandu municipality health department and subject to the same shortages experienced by the municipal plants.

5.4 Efficacy

The disinfective efficacy of chlorine is indisputable from a technical perspective. Municipal tap water with free chlorine residual levels of 0.3 mg/ml showed the expected zero bacterial counts. The efficacy of chlorine is amply demonstrated in the following results of a study conducted by ENPHO between 1991 and 1992 AD on the water distribution system in Nepal. The diagram clearly shows an increase in free residual chlorne level corresponding to a lowering in coliform levels

This and numerous other studies have proved the efficacy of chlorination by centralized municipal facilities

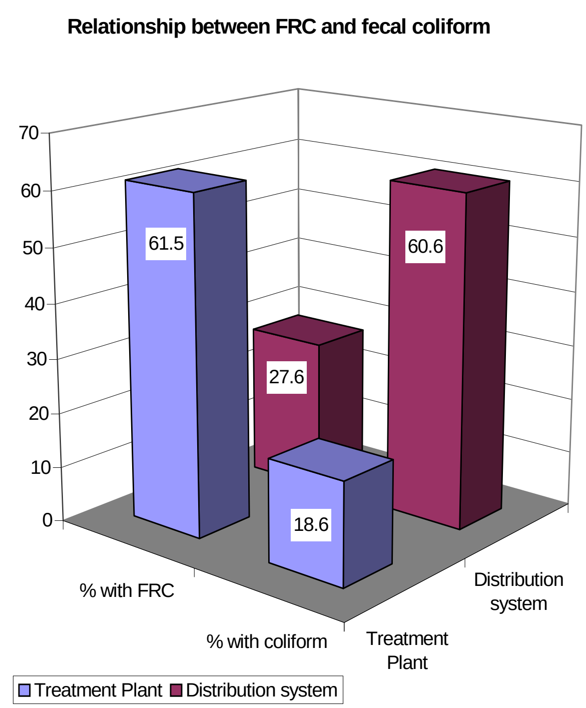

Figure 5-1: Inverse relationship between Free Residual Chlorine and fecal coliform counts in the Kathmandu Valley water treatment and distribution system (Data: Shrestha, 1995 Analysis: Wolfe, 2000)

The seasonal variability in water quality raises some concern as per the application of chlorine as a POU disinfection technique. The increase in organic contamination of the available waters during the monsoon season is a cause for concern for the application of a POU chlorination technique. This concern is due to the need for higher chlorine dosages in order to achieve break-point chlorination and the associated undesirable effects of an increased risk of trihalomethane formation and an increase in chlorine odor and taste.

5.5 Acceptability

Conversations with various Nepalese reveal a strong aversion to any sensible evidence of chlorine in drinking water. Numerous of the interviewees stated that for a chlorination regimen to be effective and applicable it would have to be undetectable to the consumers. Representatives from both the DWSS and the NWSC, cited numerous objections from the consumers when chlorination is used in the municipally supplied water.

6 ULTRAVIOLET DISINFECTION FIELD TESTS

6.1 Introduction

Ultraviolet disinfection is present in Nepal in two capacities. There are a small number of medium scale[12] disinfection plants in operation around the country, mostly as demonstration projects by proprietary manufacturers demonstrating the efficacy of their appliances (Personal communication, Lotus Group). There are also a number of proprietary POU devices sold on the market. These POU devices are prohibitively expensive by Nepalese standards. An example of such a system is the Euroguard™ system, priced at 12,500 NRS (approx. USD 225), which when compared to the average monthly salary of 1000 NRS (approx. USD 20), is clearly unattainable. Such devices are commonly found in the houses of the Nepalese elite and in the domiciles and workplaces of expatriate foreign workers (Personal Communication, Ajaya Dixit, NEWAH).

6.2 Availability

A reliable power supply is essential for the working of an ultraviolet disinfection device. As only 14 percent of all households and just 9 percent of all rural households have access to electricity (UNDP HDR, 1998), it is a far stretch to imagine this type of technology to be useful for wide scale application. There has been some research into the possibility of harnessing solar energy through photovolaic panels as means of generating the necessary electric power (Rijal *et al, 1996*). Such systems would break the dependence on the municipal power grid and allow for a much larger scale application of this type of technology. At the present moment, such devices, where available, are not cost effective and do not provide sufficient volumes of water (Rijal *et al*, 1996).

6.3 Efficacy

Due to the high cost of the device, and the unavailability of electricity, disinfection tests were not performed on these devices.

6.4 Acceptability

An acceptability study was not performed as this device was not tested or demonstrated.

[12] The Kathmandu Convention Center uses one such device (Personal Communication, Dilli Bajracharya)

7.1 Introduction

Solar disinfection is a concept and practice that is just beginning to garner attention in Nepal. Although there has been an independent field trial conducted in the Terai region (Moulton, 1999), there is no research available to date on tests in the Kathmandu Valley or its environs.

7.2 Methodology

The POU application tests were conducted on the roof of the Central Laboratory of the Nepal Water Supply Corporation in Kirtipur, Kathmandu

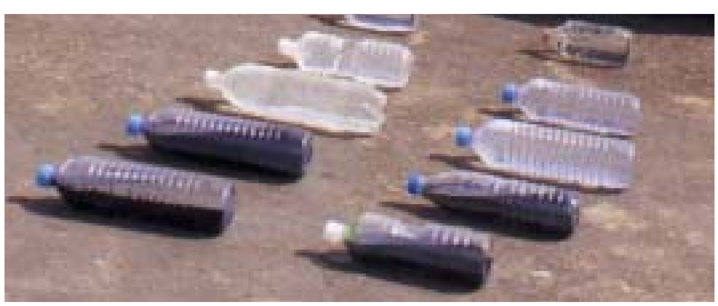

Figure 7-1: Bottles undergoing solar disinfection

The bottles tested were locally available transparent bottles used for soft drinks or bottled mineral water. Three container types were tested, untinted transparent plastic, blue tinted transparent plastic and untinted transparent glass. In experiments requiring half blackened containers, containers of the types listed above were painted black using locally purchased matte enamel paint.

The water used in the tests was bacterially contaminated local tap water, supplied by the nearby Sundarighat treatment plant. To commence the test, the bottles were washed with soap and water, thoroughly dried and filled with the raw water to be disinfected. The bottles were then placed on the rooftop of the laboratory, which consisted of a south-facing black-tarred surface with an incline of 18^{o}. Solar intensity was logged hourly using a Kipp and Zonen SOLRAD™ CM3/CC20 Solar radiation measurement system, which is responsive to wavelengths between 350nm and 1500nm.

Bottle transmissivity tests, using containers purchased in Nepal, were conducted upon the return to Cambridge. The transmissivity tests were conducted by filtering sunlight through a section of the container material and computing percent transmittance compared with unfiltered results.

In tests in which temperatures were logged, a separate representative container of each type was placed on the rooftop accompanying those used for the disinfection study in order to avoid potential contamination of the samples.

7.3 Availability

7.3.1 Containers

Transparent bottles are ubiquitous in the Kathmandu Valley. These glass and plastic bottles come in various shapes and sizes and most, if not all, are amenable to usage in a solar disinfection regime.

The specific transmittance properties of the bottle types used were unknown during the tests in Nepal, however laboratory testing upon return to Cambridge revealed the following data.

Bottle Type	% Transmittance
Transparent Glass	73%
Transparent Plastic	87%
Blue Transparent Plastic	88%

Table 7-1: Container Transmissivity Data

7.3.2 Solar Energy: Optical Component

The availability of solar energy is a less-known quantity. The data presented below is a reflection of what is currently available in the literature, complemented, in small part, by data accumulated during the January 2000 field work in the Kathmandu Valley. The data is in no way comprehensive. It is very important not to over extend the applicability of this data. In the absence of a more complete study it serves to give an initial impression of the viability of solar disinfection. However as solar radiation varies greatly with locale extensive regional data must be compiled before any final recommendation for the use of solar disinfection can be made.

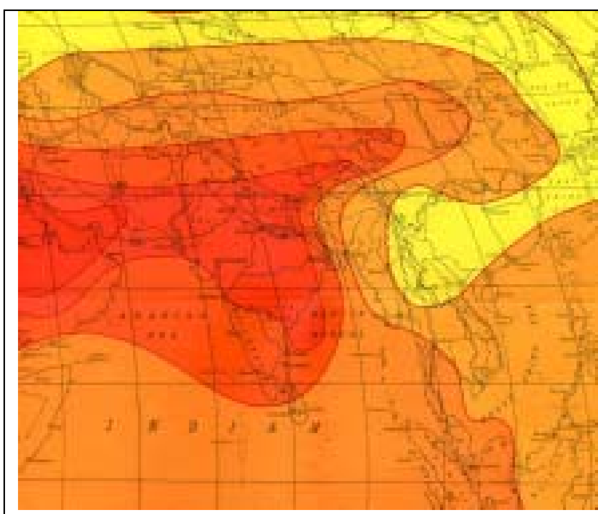

Fig. 7-2 Generalized Isolines of global radiation Nepal receiving 424 – 478 W/m^2 (Landsberg)

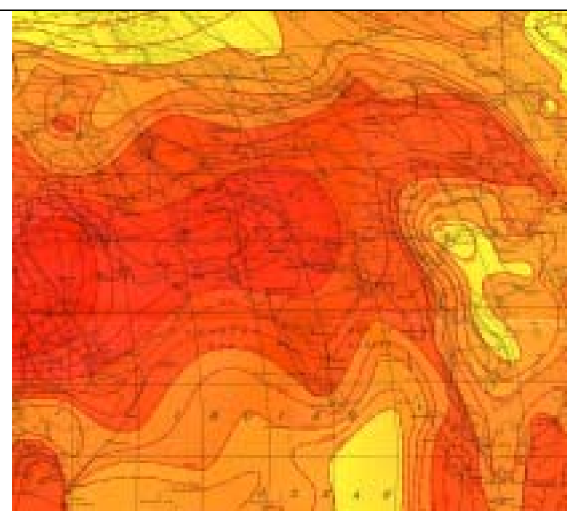

Fig. 7-3: Total Annual hours of sunlight Nepal receiving 2800-3000 hrs (Landsberg)

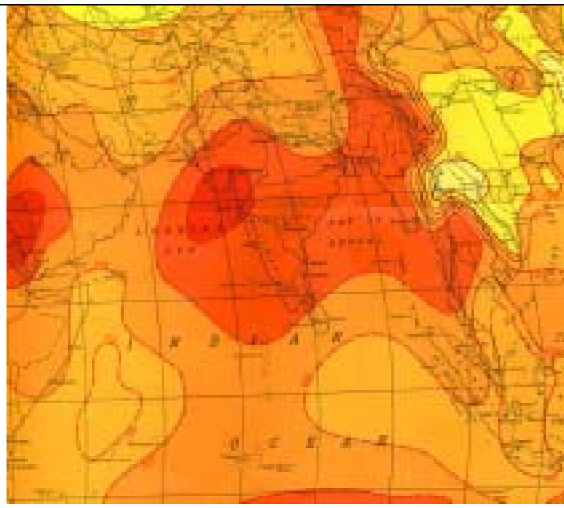

Fig. 7-4 January Hours of sunlight (mean) Nepal receiving 200-250 hrs (Landsberg)

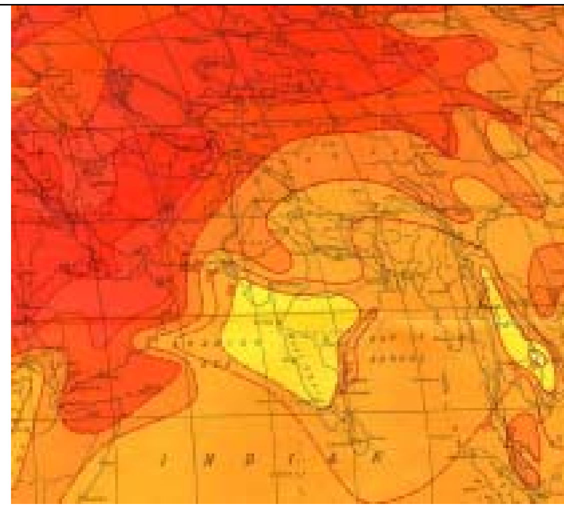

Fig. 7-5 July Mean Hours of sunlight Nepal receiving 100-150 hrs (Landsberg)

The dosage of solar radiation required for adequate disinfection in the Kathmandu Valley is not well established. Previous studies conducted in the Terai lowlands region of Nepal (Moulton, 1999) indicate that removal of indicator organisms by solar disinfection in direct sunlight required 4700 Wh/m^2 (5 or 6 hours exposure during the peak sunlight hours). The same study reports that using a blackened rack reduces the requirement to 3000 Wh/m^2, (3 to 4 hours peak sunlight) and a solar reflector reduces it further to 1000 Wh/m^2, (approx. 1 hour peak sunlight). However it is important to note that these studies were conducted in the months of April and May in the Terai region in which the climate and meteorological conditions are considerably different.

As stated earlier, latitude, geographic location, time of year, meteorological conditions, and atmospheric pollution levels are the primary determinants of the availability and intensity of solar radiation. In Nepal the average mean daily solar radiation ranges between 3800 Wh/m^2/day in January to 6000 Wh/m^2/day in July (Manni, 1982). In addition to intensity, mean hours of sunlight also vary throughout the year. In the Northern Hemisphere, the shortest days occur during the months of December and January. However as indicated in Figs. 7-4 and 7-5, the monsoon climate of Nepal causes a de-facto reversal of this trend. It is very hard to conclude whether Nepal is suitable for solar disinfection throughout the entire year, as there exist both enabling and mitigating factors to its application. For example, the months of May, June and July, in which solar radiation is at a peak, are also monsoon months with high cloud cover. The relatively clear skies of January are counterbalanced by fewer hours of available sunlight.

7.3.3 Solar Energy: Thermal Component

Seasonal average daily temperatures fluctuate greatly between the regions of Nepal ranging from the subtropical monsoon conditions in the Terai region to alpine conditions in the Himalayas. Average winter (November-March) temperatures vary from 19 ^{o}C in the southern Terai region to 13 ^{o}C in the Kathmandu Valley. Summer (April-June) temperatures range from 28 ^{o}C to 21 ^{o}C in the same regions (Nepal Ministry of Home Affairs).

The solar disinfection tests in the Terai region (Moulton, 1999) reported a water temperature increase as high as 10 ^{o}C above ambient air conditions, to a maximum of 50^{o}C. In the January 2000 Kathmandu Valley tests, both unaltered and half-blackened bottles were used to measure the solar heating effect. The results show a slight increase in temperature in the bottles, which is amplified slightly in the half-blackened bottles. The temperature did not approach the threshold temperature of 45^{o}C any test.

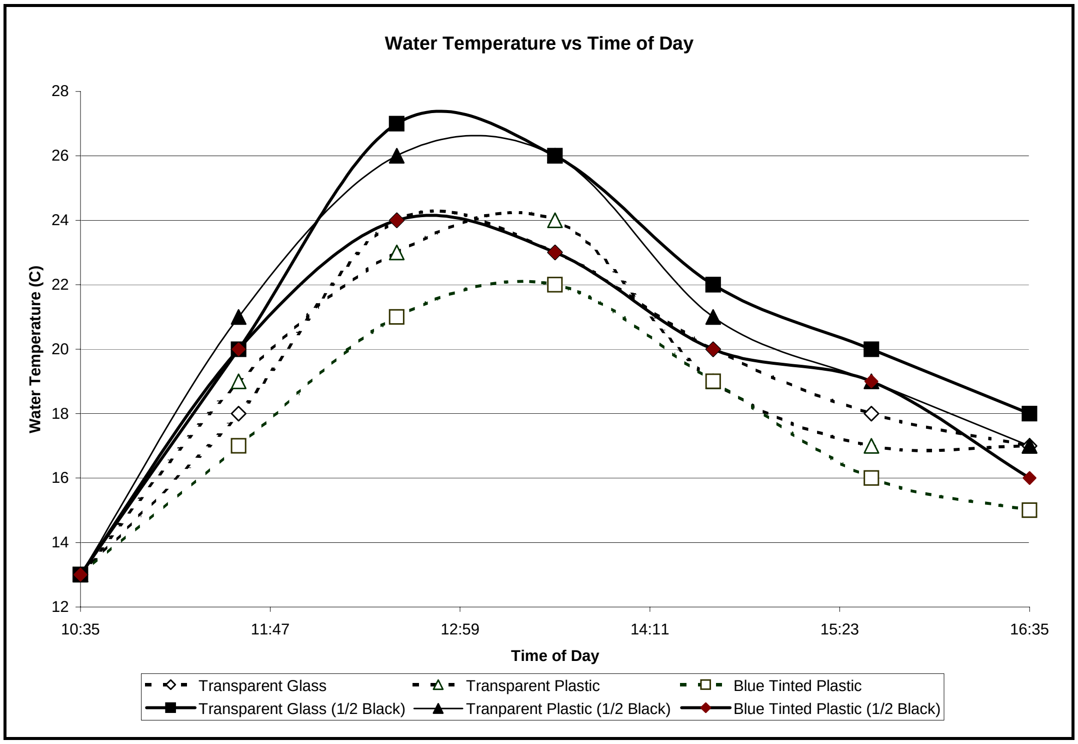

Fig. 7-6: Water temperature variation vs Time of day during solar disinfection experiments

It can be concluded that any disinfection that occurred was due to the optical aspects of sunlight alone, heightening the importance of the transmissivity of the containers, and the clarity of the water being purified.

7.4 Efficacy

Due to time and logistic constraints, only a limited number of solar disinfection field tests were conducted. This limitation on data precludes a generalization of the results by statistical or analytical methods. The individual test results will be presented case-by-case. The weather pattern was typical of the Kathmandu winter: overcast morning often but not always leading to clear skies by noon. The average ambient temperature during the testing periods ranged between 10 and 15^{o}C. There was considerable air pollution and haze.

7.4.1 Solar Disinfection Tests 17/1/00

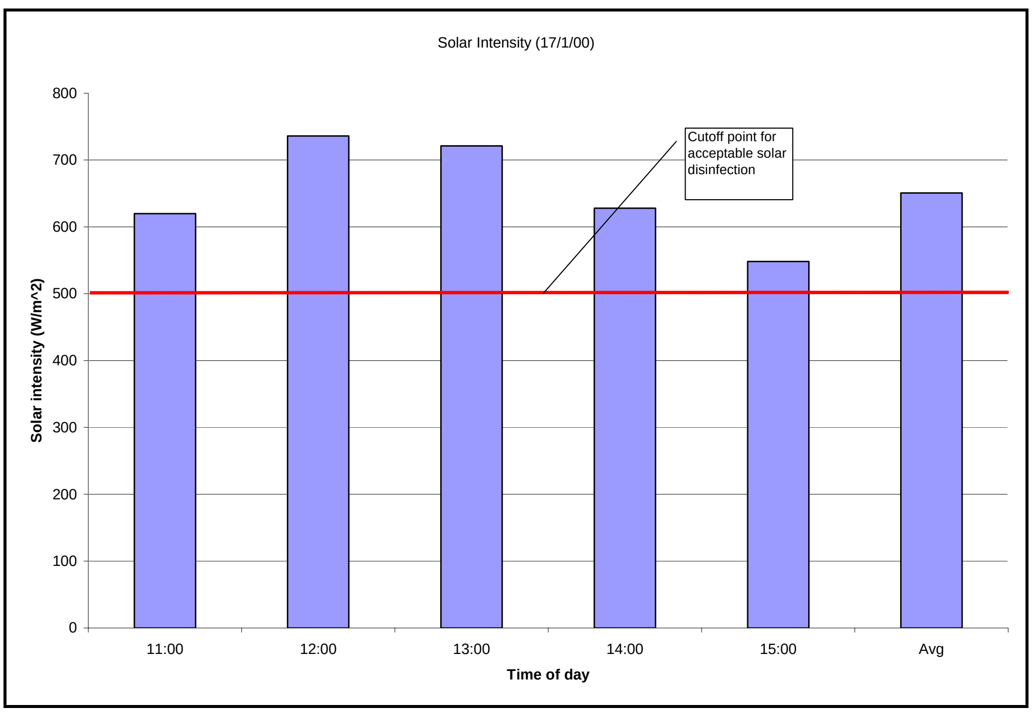

Fig. 7-7: Solar intensity vs Time of day with an indication of the cutoff threshold of 500W/m^2

Initial Conditions	
Water Source	Central Lab Tap water
Test Start time	11:00 AM
Container Types and nos.	Blue Plastic $\times 5$
Pretreatment	None
PH	7.5
Water Temperature (^oC)	13

Table 7-2: Initial Conditions 17/1/00

This initial test was conducted using five blue-tinted plastic bottles. The bottles were placed in the sun for a total of 4 hours. The solar radiation was consistently above the threshold of 500W/m^2. The disinfection results presented below in Table 7-3 indicate that some removal of H_2S producing bacteria was evidenced by the MPN test, however removal of total coliform and *E. Coli* was not achieved.

P/A test		H_2S MPN test	
Before		Before	
Total Coliform	Positive	# Positive (x/5)	5
E. Coli	Positive	# coliform/ 100 ml	> 8.0
After		After	
Total Coliform	Positive	Incubation time (hrs)	24
E. Coli	Positive	# Positive (x/5)	3
		# coliform/ 100 ml	4.6

Table 7-3: Microbial Results 17/1/00

7.4.2 Solar Disinfection Test 20/1/00

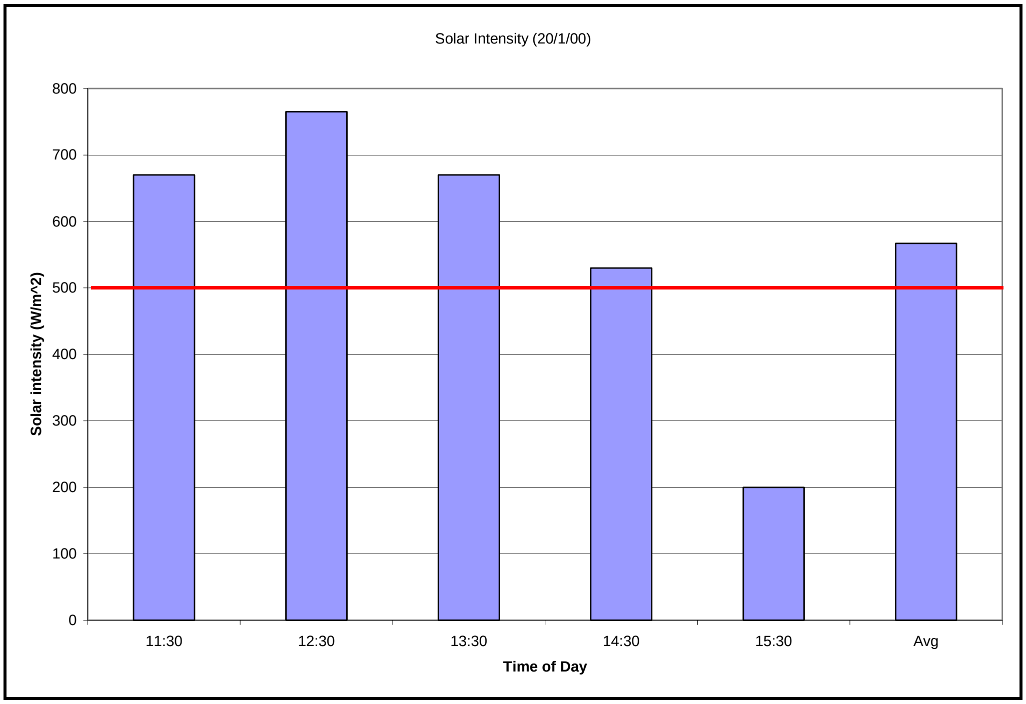

Fig. 8-7: Solar intensity vs Time of day 20/1/00

Initial Conditions	
Water Source	Central Lab Tap water
Test Start time	11:30 AM
Container Types and nos.	Blue Plastic ×4 Untinted Plastic × 4
Pretreatment	None
PH	7.4
Water Temperature (C)	13

Table 7-4: Initial Conditions 20/1/00

In this trial untinted transparent plastic bottles were used in addition to the blue-tinted bottles used previously. The solar radiation pattern was similar to the previous day and the bottles were irradiated for a total of four hours. The microbial removal results shown in Table 7-5 demonstrate a removal of H_2S producing bacteria, and the survival of the total coliform and the *E. Coli*. Within the sensitivity of this experiment, there was no noticeable difference between blue tinted and untinted containers.

P/A test	Blue Plastic	Untinted Plastic
Before		
Total Coliform	Positive	Positive
E. Coli	Positive	Positive
After		
Total Coliform	Positive	Positive
E. Coli	Positive	Positive

H_2S MPN test	
Before	
# Positive (x/5)	5
# coliform/ 100 ml	> 8.0
After	
Incubation time	24
# Positive (x/5)	All negative
# coliform/ 100 ml	< 1.1

Table 7-5: Microbial Results 20/1/00

7.4.3 Solar Disinfection Test 23/1/00

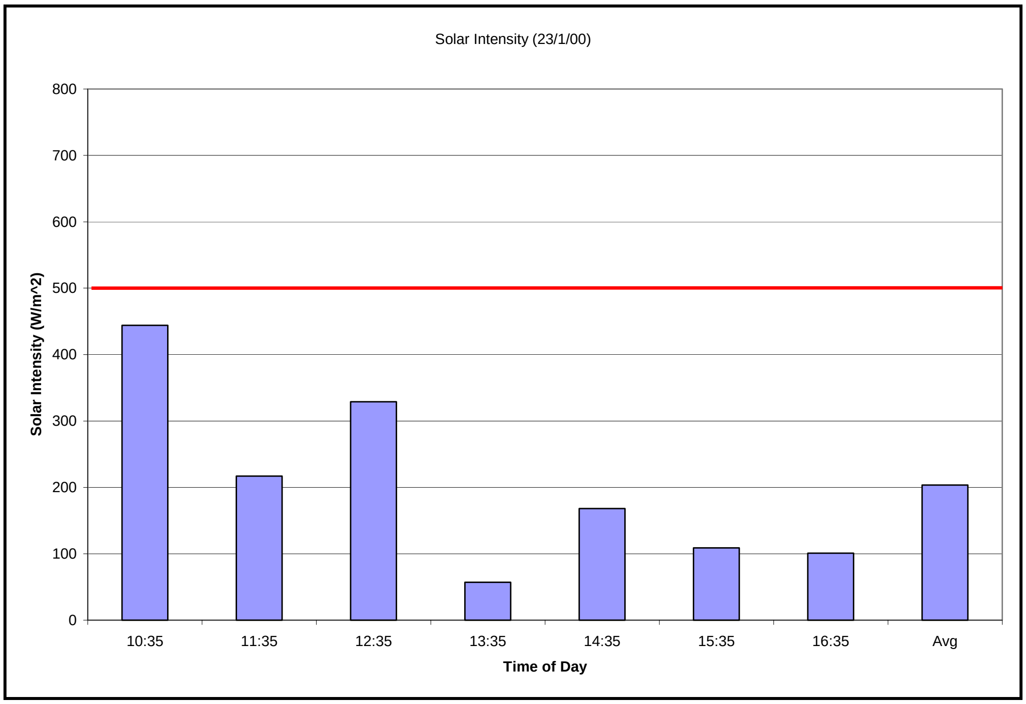

Fig. 8-8: Solar intensity vs. Time of day 23/1/00

On this day the tap water samples used as a raw water input to the experiments was chlorinated[13]. The microbial results of this trial are not usable. The meteorological conditions on the day of this trial were also particularly adverse. The heavy cloud cover continued throughout the day, leading to lower solar radiation readings.

[13] The Sundarighat water treatment plant, which supplied the water supply to the NWSC Central Laboratory where the MIT Nepal Water Project team conducted its experiments was a poorly operated and maintained treatment plant which during the month long extent of the study chlorinated only on one day 23/1/00, the day of this test

It is interesting to note that in spite of the adverse conditions a significant amount of dechlorination was observed in the solar treated samples as compared to the non-irradiated control. A control sample which had been kept indoors away from direct sunlight, showed a free residual chlorine level of 0.4 mg/l at the end of the testing period, while those exposed to the sun showed zero free residual and zero total chlorine levels. The data acquired from this test can be applied to a variant of the solar disinfection method, dubbed the Halsol method (see Appendix A) in which highly polluted water is treated with high doses of chlorine prior to dechlorination by solar irradiation.

7.4.4 Solar Disinfection Test 24/1/00

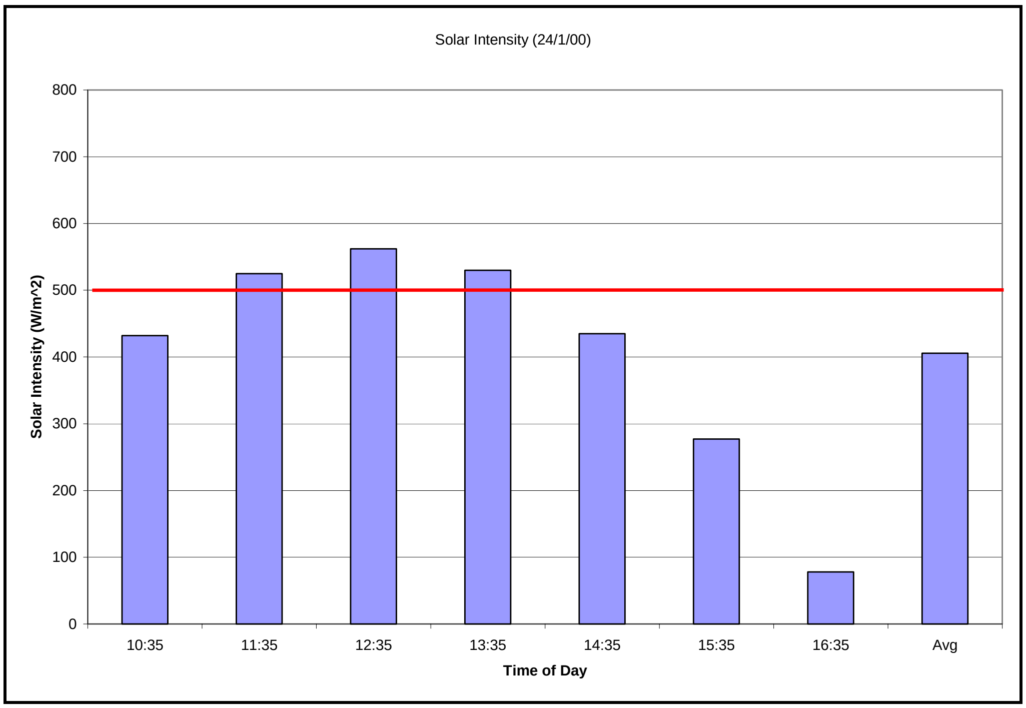

Fig. 8-9: Solar intensity vs Time of day 24/1/00

Initial Conditions	
Water Source	Sundarighat Inflow Water (untreated)
Test Start time	11:30 AM
Container Types and nos.	Blue Plastic (×2 Plain ×2 half black) Untinted Plastic (×2 Plain ×2 half black) Untinted Glass (×2 Plain × half black)
Pretreatment	None
PH	7.5
Water Temperature (C)	11
Weather Conditions	Overcast/Clear

Table 7-6: Initial Conitions 24/1/00

The following experiment was conducted in order to explore the effect of using half-blackened bottles on solar disinfection. Transparent, untinted glass containers were also introduced in this experiment. Four samples of each type of container, two painted half black and two unpainted were filled with water directly from the inflow of the Sundarighat treatment plant (to avoid chlorine). The bottles were irradiated for a total of five hours.

The microbial results show little difference between the painted and unpainted bottles as the upper limit of temperatures attained was 26^{o}C and the accepted threshold for the heat effect is 45^{o}C. Significantly however, removal of *E. Coli* was effected in the transparent glass and plastic containers and some of the blue tinted containers. The MPN results conformed to expectations with a total removal of H_2S producing bacteria.

P/A test	All Samples
Before	
Total Coliform	Positive
E. Coli	Positive

P/A test	Blue Plastic	Untinted Plastic	Untinted Glass
After		Untinted Plastic	Untinted Glass
Total Coliform	Positive	Positive	Positive
E. Coli	Positive	Negative	Negative
After (1/2 Black)			
Total Coliform	Positive	Positive	Positive
E. Coli	Negative	Negative	Negative

Table 7-7: Presence Absence Tests Results 24/1/00

H_2S MPN test	
Before	
# Positive (x/5)	5
# coliform/ 100 ml	> 8.0
After	
Incubation time	24
# Positive (x/5)	All tests Negative
# coliform/ 100 ml	< 1.1

Table 7-8: Most Probable Number Test Results 24/1/00

7.4.5 Solar Disinfection Test 25/1/00

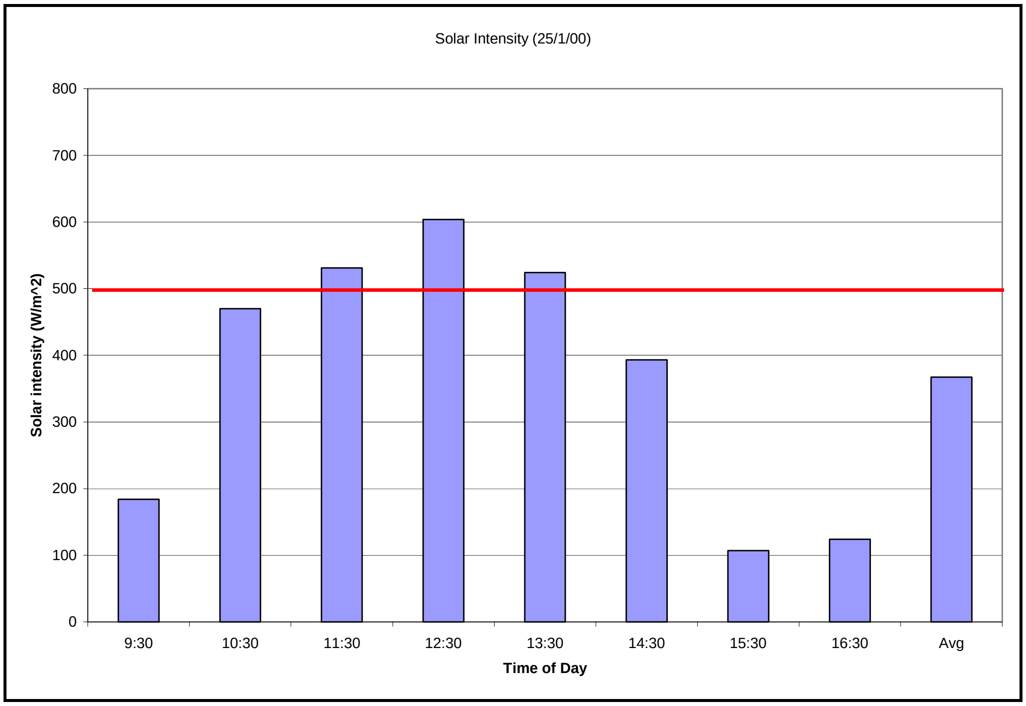

Fig. 8-10: Solar intensity vs Time of day 25/1/00

Initial Conditions	
Water Source	Sundarighat Inflow Water (untreated)
Test Start time	11:30 AM
Container Types and nos.	Untinted Glass (Plain ×6) Untinted Plastic (Plain ×6)
Pretreatment	Filtration (Bajaj, Thimi, IFP)
PH	7.5 (8.4 for the IFP samples)
Water Temperature (C)	13
Weather Conditions	Overcast/Clear

Table 7-9: Initial Conditions 25/1/00

A possible application for solar disinfection is as a second round of purification following filtration. The advantages of prefiltration are the lowering of turbidity and a reduction in the amount of bacterial contamination, both of which are complementary to solar disinfection.

In order to determine the efficacy of solar disinfection in this capacity, experiments were conducted using water that had been pretreated by filtration in one of three different filters[14], Bajaj, Thimi, and IFP.

The Bajaj filter is a locally available ceramic candle filter imported from India, the Thimi filter is a locally manufactured ceramic candle filter and the IPI Purifier, manufactured in Florida, is a two step disinfection-filtration system which filters chlorinated water through a combination of string wound and activated carbon filters.

The microbial results show that for water treated by the Bajaj filter and the Thimi filter, there was an improvement in microbial water quality following solar treatment. In the case of the Bajaj filter one trial, even achieved total removal of Total Coliform, *E.Coli* and H_2S bacteria. The result from the Thimi filter was unchanged with respect to total coliforms, but a removal of and H_2S bacteria and *E. Coli* was effected. The IFP filter results were Total Coliform, *E.Coli* and H_2S bacteria free before treatment and experienced no change in microbial quality post solar treatment.

P/A test	Bajaj	Thimi	IFP
Before			
Total Coliform	Positive	Positive	Negative
E. Coli	Negative	Positive	Negative

P/A test	Untinted Plastic (Bajaj)	Untinted plastic (Thimi)	Untinted Plastic (IFP)
After			
Total Coliform	Negative	Positive	Negative
E. Coli	Negative	Negative	Negative
After	Untinted Glass (Bajaj)	Untinted Glass (Thimi)	Untinted Glass (IFP)
Total Coliform	Positive	Positive	Negative
E. Coli	Negative	Positive	Negative

Table 7-10: Presence Absence Test 25.1.00

[14] For more information on the POU Filtration study see Sagara J, Study of Filtration for Point-of-use Drinking Water Treatment in Nepal

H_2S MPN	
Before	
Bajaj	
# Positive (x/5)	1
# coliform/ 100 ml	1.1
Thimi	
# Positive (x/5)	1
# coliform/ 100 ml	1.1
IFP	
# Positive (x/5)	0
# coliform/ 100 ml	<1.1

H_2S MPN	
After	
Bajaj	
Incubation time	24
# Positive (x/5)	0
# coliform/ 100 ml	<1.1
Thimi	
Incubation time	24
# Positive (x/5)	0
# coliform/ 100 ml	<1.1
IFP	
Incubation time	24
# Positive (x/5)	0
# coliform/ 100 ml	<1.1

Table 7-11: Presence Absence Test 25/1/00

7.4.6 Solar Disinfection Test 26/1/00 – 27/1/00

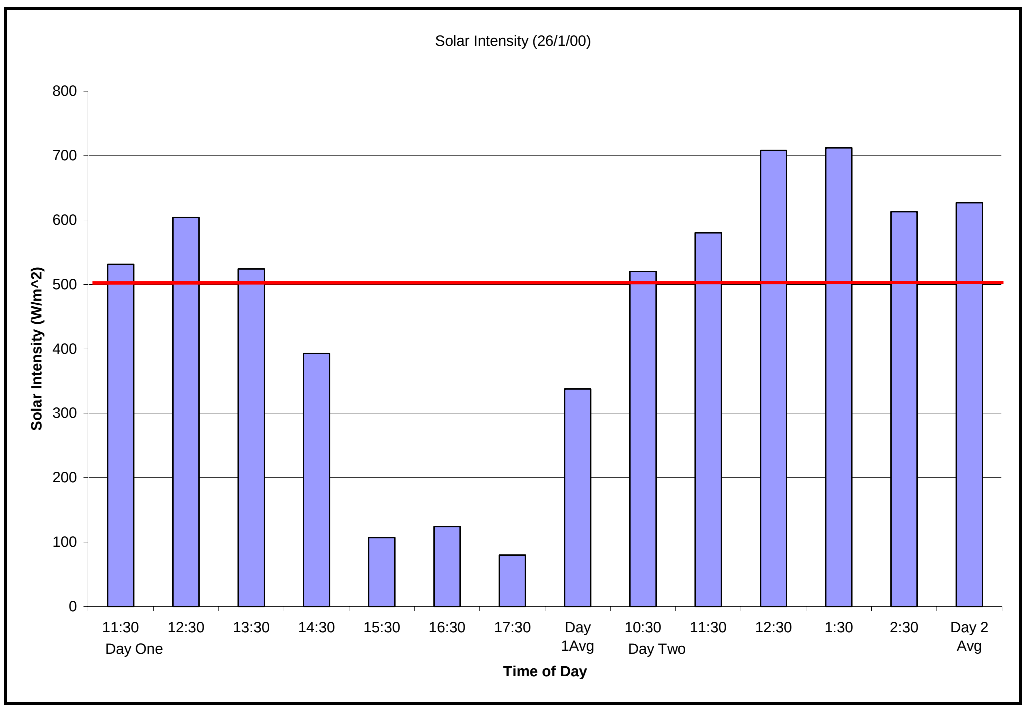

Fig. 8-11: Solar intensity vs Time of day 26/1/00 – 27/1/00

Initial Conditions	
Water Source	Central Lab Tap Water
Test Start time	11:30 AM
Container Types and nos.	Untinted Glass (Plain ×4) Blue Plastic (Plain ×4) Untinted Plastic (Plain ×4)
Pretreatment	None
PH	7.8
Water Temperature (C)	11
Weather Conditions	Overcast/Clear

Table 7-12: Initial Conditions 26/1/00

Extending the exposure period by leaving the containers out for two consecutive days is another possible method for enhancing disinfection efficacy. Bottles were exposed to the sun for approximately 11 hours. The results of this test were the most promising of all the trials performed. Removal of *E. Coli* was achieved in twelve out of twelve tested samples. Total coliform removal was achieved in nine out of twelve tested samples. The blue plastic containers performed the least effectively in this trial with remaining indications of total coliform contamination. The reason for this performance lag is unknown and is in need of further study.

P/A test	
Before	
Total Coliform	Positive
E. Coli	Positive

P/A test	Untinted Plastic	Untinted glass	Blue Plastic
After			
Total Coliform	Negative	Negative	3 Positive 1 Negative
E. Coli	Negative	Negative	Negative

Table 7-13: Presence Absence Test 26/1/00 – 27/1/00

7.5 Acceptability

Solar disinfection of drinking water is part of the traditional Nepalese treatment regimen and apparently has been used in villages for centuries if not longer (personal communication, Dilli Bajracharya). The traditional method involves leaving water exposed to the sun in wide mouthed ceramic containers for one day prior to consumption.

The conformity of the studied technique with local tradition increases the possibility of acceptance and adoption of this type of treatment into day-to-day practice.

The possibility of being able to disinfect their water with little more than an empty bottle and the sun was greeted with much enthusiasm by the majority of the people encountered in the duration of the study.

8 CONCLUSIONS OF THE POINT-OF-USE DISINFECTION STUDY

The table below offers a comparative summary of the compliance of the three point-of-use disinfection techniques with the criteria of the study. This table highlights a fundamental disharmony between the technical and socio-economic spheres of analysis. It is this disharmony that adds such complexity to the challenge of providing safe water in Nepal.

Ultraviolet disinfection is a case in point. Technically speaking it is the best performing point-of-use disinfectant. All things considered, ultraviolet disinfection's socio-economic viability is virtually nil. This non-viability effectively removes the option of using ultraviolet disinfection as an immediate solution to the safe water scarcity in Nepal.

Deciding between chlorination and solar disinfection is rather more difficult as both techniques have advantages and drawbacks to their use.

Laboratory testing has proven and reiterated that chlorination is indisputably a superior disinfectant with regards to pathogen removal efficacy. Providing users with almost guaranteed pathogen removals, secondary protection against reinfection and a handy residual test for water safety, chlorine appears to be a panacea in waiting. The inconsistent performance of solar disinfection in this regard, is a significant drawback. The information collected in the course of the January 2000 field research is ample cause for a reassessment of the above conclusion. Under real-life conditions in Nepal the superior technical performance of chlorine is tempered by its relative inaccessibility due to logistic, safety and esthetic concerns. The real time effectiveness and penetration of chlorination is low, despite numerous, long running, attempts at implementing it throughout Nepal (Personal communication, ENPHO, UNICEF). Solar disinfection on the other hand, requires very little by means of equipment, and no outside chemical or power supplies. It also has the advantage of conformity with traditional local practice. The water quality improvement may not be complete, but even in a worst case scenario this technique will not reduce water quality.

	Chlorine Disinfection	Solar Disinfection	Ultraviolet Disinfection
Technical Criteria			
Effective on many types of pathogens and on whatever numbers may be present in water	✓	✘ †	✓
The temperature and pH range in which the disinfectant will be required to operate must be adequate.	✓	✓	✓
The disinfectant must not make the water either toxic or unpalatable	✘ ‡	✓	✓
The disinfectant must be safe and easy to handle	✘	✓	✓
The concentration of the disinfectant (if chemical) must be minor	✓	✓	✓
The disinfectant must provide residual protection against possible recontamination	✓	✘	✘
Socio-economic Criteria			
Cost; the units must be affordable to all, especially those in the lower income brackets as they are less likely to have access to treated water	✓	✓	✘
Adaptability to local conditions, regional variations in water usage patterns and water quality must be considered	✓	✓	✘
To the extent possible the utilization of specialized equipment in the treatment process should be limited to that produced locally	✘	✓	✘
Indigenous materials and manufacture should be used to reduce costs and bolster the local economy	✘	✓	✘
Influence of local traditions, customs and cultural standards	✘	✓	✘
Influence of national sanitation and pollution policies	✓	✓	✓

† Data is not available for many types of pathogens, field testing inconclusive
‡ Risk of accidental overdose or misapplication, THM formation

Table 8-1: Point-of-use method compliance with study criteria

As the conditions in Nepal are neither ideal nor static, an adaptive solution to the current crisis must be advocated. In areas in which chlorine is available, it remains the most effective and comprehensive point-of-use treatment method. In times and areas in which chlorine is either unavailable or infeasible, due to any number of the complications described above, solar disinfection can be substituted as an interim solution.

In areas that receive adequate levels of solar radiation year round[15], it may be possible to rely entirely on solar disinfection. In areas that experience sufficient solar radiation levels for a portion of the year it is possible to use solar disinfection for that part of the year, supplemented by chlorination when the solar radiation levels drop below a threshold.

[15] Such areas remain to be determined due to a lack of data on year round solar radiation patterns

SECTION III

SUGGESTIONS FOR A COMPREHENSIVE POINT-OF-USE TREATMENT SYSTEM IN NEPAL

9 DRINKING WATER IN ITS SOCIETAL CONTEXT: NEPAL

9.1 Introduction

Assessing the role of drinking water within its societal context is a difficult task. The conceptual value of water varies greatly amongst the different strata of society. Even on the household level, there often exists conflicting conceptions of the value of water according to the profession, age and sex of the respondent (Dixit *et al,* 1999; Brooke, 1999). For example, municipal authorities may consider water provided to a community through a communal tap or well as a free service in that there are no charges for its use. This view may indeed be shared by those elements of society not involved in the collection and distribution of water. However, to those responsible for collecting the water, a task that falls mainly upon women and children in Nepal, the effort expended collecting water is considerable, making water procurement a drain on their resources. The onerous nature of this task implies that households generally make do with as little water as possible (UNDP HDR, 1998). This is particularly true of the hill and mountain regions, and not rare in the urban centers amongst the less affluent strata of society. The level of per capita consumption of water, therefore, is very low. The highly limited use of water, is one of the principal causes of a low level of sanitation.

9.2 Need for a socially conscious approach in drinking water supply

The last fifty years of water management in Nepal has been the story of an unfolding disaster. Water scarcity and unavailability in Nepal is the result of abuse and wastage of water and general mismanagement of natural resources. Throughout the Nepal, the available water supplies of cities and villages have declined in quality and quantity (Dixit *et al*, 1999).

The past and current solution to this problem has been to implement large-scale infrastructure intensive projects to mechanically bolster supply[16]. These efforts have almost invariably ignored existing scientific and social knowledge and have typically ended up aggravating the problem (Brooke, 1999). The last half century of construction led water development has failed to address the basic sources of the people's suffering. It has not provided wholesome drinking water to rural, urban and suburban areas. On the contrary, misplaced development priorities have ignored the diverse social contexts of water to damage the foundations of social and community life. The institutional neglect of traditional water supply and management systems, in favor of systems modeled after those in developed countries has led to a decline of traditional methods (Mendis, 1999). The ill managed and misapplied methods of the central planners however are frequently not adequate to meet demand.

Decisions on massive water development projects are often modeled on water regimes developed in other regions and on limited or parochial databases. In the extreme climactic variations in Nepal, these models often do not work, particularly in the mountainous regions. Given the present plans, access to wholesome water will remain a mirage for the majority.

Another issue of concern is that decisions in water management are usually state-centric rather than community-centric. Centralization of water management and water development, while successful in planning for and sometimes implementing large scale,

[16] The Melamchi River project is the latest such schemes. It involves digging a 27 km long tunnel to channel water from the Melamchi river in an a valley adjacent to the Kathmandu Valley. For more information see Melamchi: Pipe Dream in the Pipe Line, Shrestha MS

capital intensive projects, has led to bureaucratic neglect of local needs. Often funded by international donors through government agencies, such centralized water systems are hostile to local initiatives in matters of water crisis and water security. Consequently, decisions about water are disassociated from its actual users. Due to this and other effects of uneven development, farmers, artisans and others in rural areas have frequently been forced to migrate to overcrowded cities themselves without adequate infrastructure, employment, housing and sanitation. In the meanwhile, overcrowded cities generating organic wastes add to the level of pollution and further strain the supply of fresh water.

Science and technology alone are not sufficient to explain the complex, interactive processes shaping the relationships among water, nature and human intervention. The natural sciences may be adequate to explain the physical and chemical processes involved in harnessing or developing water resources for human use. It cannot however explain the social contents of water management or the institutional responses needed for just and equitable water supply. Most water management takes place at the level of the individual, the household and the community; arenas that are not given much weight by the central planning authorities of municipal utility offices.

On the other hand it must be recognized that a social or political approach to water supply issues is also insufficient. Purely social approaches to water supply issues are not informed by technical concerns and often are skewed by unfounded value judgements and partisan allegiances.

The solution to the water management and resource allocation problems of a developing country like Nepal lies in a two-way dialogue between the central authorities and the consumers. There is a need to inform and empower the systems of water use at the grass roots level with better science, including traditional sciences, and to sensitize the science of water management to social realities.

9.3 Challenges in implementation of reform

Decision-makers of water management are frequently unwilling to act on a project for water quality betterment except in terms of supply augmentation through technical interventions. There is a willful neglect of the reality that new and sophisticated technologies may allow control over the movement of natural water, but cannot separate water from society. Thus, water use continues to take place within existing asymmetry of wealth, knowledge and information, conflict and struggle for power. Global capital, seeks quick returns, not bottom up initiatives necessary for self-reliant change and thus cannot be relied on to implement any change in this sector. Grassroots organizations are often fragmented and partisan, without the necessary rigor to develop sustainable institutions and ventures.

Increased dialogue between the central authorities and the populace is the only feasible solution. The development process is in dire need of reconsideration from the perspective of the underdeveloped nation, as opposed to the directives of the developed world.

10 POINT-OF-USE TEATMENT SYSTEMS CURRENTLY IN USE

According to numerous sources, most households in the Kathmandu Valley, with sufficient means, apply point-of-use treatment to water prior to consumption. This POU treatment overwhelmingly consists of boiling followed by filtration. The most commonly used point-of-use water filter are Indian manufactured 2 container systems employing a ceramic candle filter.

Treating water in this fashion, though effective, is relatively expensive. Prices for Indian manufactured filter systems range from US$10 to $20. Operating costs are substantially higher due to the need for regular ceramic candle replacement every 6-12 months at the cost of US$1.50 to US$2.00 a piece. Disinfection by boiling adds to cost of treatment in both economic and environmental terms.

Information varies with respect to usage patterns in the Kathmandu Valley region, numbers cited for the percentage of population using such a technique range between 30 and 90% (personal communication, representatives of several NGOs and INGOs). However, with the price of an imported filter system being between 5 and 10% of the average annual household income, it is likely that the lower end of the range is more accurate.

In remote rural areas where most people live at a subsistence level and have little or no disposable income, buying an imported filter is out of the question. Although market distribution channels appear to exist in all areas, penetration of the product is low in rural areas because of the high cost. In rural areas, imported filters are often status symbols, affordable only to the wealthier stratum of the population, which represents less than 10% of the populace.

11 ALTERNATIVES TO THE CURRENT SYSTEM

11.1 Introduction

A point-of-use treatment system, consisting of a Nepalese ceramic candle filter followed by one of two possible disinfection options offers a possible alternative drinking water treatment regimen for the Nepalese households. This proposed system consists of a two-step process. Water is filtered in order to reduce the turbidity level and disinfected for microbial safety using either chlorination or solar disinfection. The advantages such a system offers over those currently in place are its affordability, availability and potential for self-sustainability.

11.2 Water treatment system components

11.2.1 Filters

Filtration is a simple and effective method of treating drinking water. In tests run in the Kathmandu Valley (Sagara, 2000) three different filter types were tested for viability as point-of-use treatment devices. It was determined that though effective in reducing turbidity, microbial removal was incomplete. Of the filter types tested, a locally manufactured ceramic candle filter was discovered to be the most affordable in initial and usage costs.

The currently available ceramic filters in Nepal do not have any disinfection properties. In a laboratory experiment, colloidal silver coating was applied onto the locally manufactured ceramic filter candles in order to improve their microbial removal efficiency. It was proven in the experiments (Sagara, 2000) that colloidal silver coating removes microbial contaminants in water. However, it has not been determined whether the effectiveness of colloidal silver lasts after continuous use of the filter. Thus, a second barrier is recommended in combination with the ceramic filter in order to ensure that the water is free of microbial contamination.

11.2.2 Disinfection

Chlorine, when available, is the disinfectant of choice. Chlorination of prefiltered water decreases the risk of THM formation.

Solar disinfection can be used as a disinfectant in cases where chlorine is not available and where available solar radiation is above a specified threshold ($500 W/m^2$). With turbidities above 200 NTU absorbing as much as 99% of the incident radiation within the first centimeter of optical path, prefiltration would be greatly beneficial to this process, by reducing the turbidity and the initial microbial counts.

11.3 Steps for Application of the Alternative System

The use of a two-step, filtration-disinfection process is a simple and effective method of treating drinking water on a household scale. The two-step process appears to be easily adaptable into the daily routine of water collection and treatment and can be operated without a power supply.

11.3.1 Hardware Procurement

One of the primary factors determining sustainability is the use of locally available/manufactured materials. Therefore for a program of water treatment to be sustainable, it must be adaptable to the local availability of materials.

The ceramic candle filters can be manufactured locally. They are currently produced by Nepal Ceramics Co-operative in Thimi, a small town located in the east of Kathmandu city. The manufacturing technique utilizes traditional ceramics manufacturing skills, is simple and is potentially transferable to other locations throughout Nepal. The locally available filters are significantly cheaper than the imported filters currently in use.

The requirements of disinfection vary with the method applied. Both chlorination and colloidal silver require the importation or manufacture of the chemicals. Solar disinfection requires only transparent bottles that are generally readily available, and might otherwise be a source of pollution.

11.3.2 Education and Training

Due to the decentralized nature of point-of-use treatment, the assurance of compliance of the final treated product is ultimately in the hands of the homeowner. In order to ensure the effectiveness and sustainability of a point-of-use treatment system, a comprehensive program of education and training in both basic hygiene and the manufacture, operation and maintenance of the POU system must be instituted.

The importance of basic sanitation must be addressed prior to the implementation of the point-of-use treatment project. UNICEF-Nepal and the Department of Water Supply and Sewerage of the government of Nepal are currently carrying out such attempts in communities throughout Nepal. They have assigned so called women "motivators" in each community, whose responsibility is to promote the awareness on sanitation issues and to educate the community.

The issue of water and sanitation is a convoluted one in Nepal. According to numerous sources, the unsanitary household condition is considered to be a prime contributing factor to the Nepalese drinking water contamination. However it is frequently acknowledged that the scarcity of clean water is responsible in part to the low levels of hygiene. In addition data collected during the MIT Nepal Water Project field study (Wolfe, 2000) has illustrated that regardless of the hygiene levels in the household, the water supply itself is frequently contaminated.

Nonetheless improvements in the household hygiene level would reduce the risk of further contamination of the drinking water post-treatment or "between container and mouth".

Figure 11-1: Picture of a Nepalese Potter

Traditional pottery manufacturing skills, practiced throughout Nepal, can be utilized for local manufacturing of the ceramic candle filters. A training program for local potters can provide the necessary techniques for manufacturing the ceramic candle filters. The manufacturing process itself is quite simple and thus can easily be acquired by skilled potters.

Furthermore, local manufacturing also eliminates the needs for long distance shipping of the finished product. The ceramic filters are fragile and susceptible to breakage during transportation, making local manufacturing highly desirable.

Chemical supplies required for chlorination and colloidal silver treatment pose a challenge to the sustainability of this proposed POU treatment system, as they are not currently locally manufactured and the cost of importing the chemicals may be prohibitive.

In the case of solar disinfection, transparent containers are readily available throughout the Kathmandu Valley and its surroundings

Once the supply of the treatment system components is secured, the education program must be implemented to teach the homeowners to correctly use the point-of-use treatment system. The proposed system consists of very simple processes; however, education is necessary to ensure effective treatment of water and a long-erm use of the system by the users. The filter candles must be cleaned and changed regularly.

11.3.3 The Treatment Regimen

The supplies necessary to implement this treatment regimen are one ceramic candle filter system and approximately 10 transparent containers.

Raw water is first obtained from a source using a clean container. The water is run through the filter system. The filtered water is subsequently collected in the transparent plastic containers by decanting through the spigot into the plastic bottles. If chlorine is available then it can be added directly to the plastic containers. The plastic containers allow for more accurate dosing and the possibility of applying the Halsol method of dechlorination if desired[17].

If solar disinfection is to be applied, then two or more sets of containers, each set being enough for one day's worth of consumption, are to be used. These sets are to be cycled between exposure and use. As one set is being exposed to the sun, a second set that had

[17] Appendix A

been irradiated on the previous day would be ready for consumption. Once the cycle is set in place, it is self-maintaining.

The Nepalese women and children collect water in the mornings. Instead of consuming the raw water it should be put directly through the filters. At the end of the day, the filtered water is filled into the empty containers that had been in use during the day and the newly filled containers are exchanged with containers on the roof which are brought in to cool overnight for consumption the following day.

11.4 Support and Follow-up

The dissemination approach of the treatment method advocated here, must be community oriented, open, flexible and continual. It must be based on the knowledge of the targeted communities, their needs and priorities and propose solutions tailor-made to their problems.

This approach has little chance of succeeding in the long term without the participation of the potential users of the technology. A project should involve participation right from the beginning and start with an evaluation of the traditional use of water by the target users.

Strengthening of local skills is essential if the rural Nepali communities are to efficiently control and manage their own initiatives. Development of human resources, special training programs and periodic field visits by supervising personnel are therefore key elements to any such treatment program.

It is imperative that a program allows flexibility within its operational structure. It is essential that communities and program personnel are provided with training to react to changes in local skills, conditions and opportunities. This will require the setting up of special follow-up programs in accordance with developmental trends.

The members of the communities targeted must be trained in the application of the new water treatment process, preferably by fellow community members. Peer education is an approach that enhances communication on a community level. This approach consists of conducting training sessions for various community members (men and women) to promote the project. These community education workers will transmit through house visits and public meetings clear and simple messages in their native tongue. Parts of rural Nepal already have such a network in place. The women "motivators" mentioned earlier perform just such a task at the behest of the DWSS and UNICEF-Nepal, with regards to health and sanitation. In a field trip to the Kavre district of Nepal in January 2000, a demonstration of the various components of the water treatment system was held before a group of these "motivators". Their opinions as per the feasibility and viability of such a system was then solicited. A majority stated that they were amenable to performing such treatment themselves and teaching it to others, provided it was affordable and not unduly burdensome.

APPENDICES

Appendix A: Halogen and Solar disinfection (HALSOL)[18]

Treating water with large amounts of sodium hypochlorite or iodine solution and subsequent exposure to solar radiation dubbed "halsol" was developed at the American University of Beirut (1979-1982). It is intended to be an expedient disinfection method for small volumes of heavily polluted waters with the concomitant removal of excess halogens by solar irradiation. This would utilize the well established disinfection effects of chlorination while avoiding taste and odor complaints.

Batch trials were conducted in the American University of Beirut in 1982 using up to 5 L of halogenated water containing chlorine or iodine residuals of > 7mg/L. The water was exposed to sunlight in transparent containers made of colorless or blue tinted glass or plastic, and showed efficient halogen removal. For instance the T50 and T99 values for dechlorination were 11 and 72 minutes (32 and 215 minutes for deiodination) respectively. In contrast the decay reaction occurring under normal room illumination was slower and in complete darkness retarded it(Acra *et al*, 1990). The percentage mean values for the photochemical decomposition of chlorine residuals regressed exponentially against the specific wavelengths of light that yield at least 50 % transmittance, revealed that

- The relative effectiveness of solar radiation decreased with wavelength in the 310-550nm range
- Most of the chlorine residual decomposed photochemically was largely accounted for by solar UV-A

An inverse linear relationship between total chlorine residual (TCR, percent) and chlorinated water temperature T in the range of 20-70 C was observed. The relevant linear expression is as follows

$$TCR = 109.5 - 0.47T$$

Because the rise in temperature of water exposed to sunlight did not generally exceed 10C in experiments up to 180 min , the major dechlorination was considered to be due to solar radiation.

[18] Adapted from Acra *et al* 1990

As TCR diminished with the length of exposure initial pH also decreased. This is presumed to be induced by the phototransformation of weak HOCL to the strong HCL liberating Oxygen

$$NaOCl + H_2 \rightarrow NaOH + HOCl$$
$$2HOCl + \text{sunlight} \rightarrow 2HCl + O_2$$

The linear expression derived from this is

$$pH = 7.78 + 10E - 3TCR$$

It was found that an intervening glass reduced the photodechlorination process. The process was 2.5-3 times more efficient for containers placed in front of a closed glass window than those placed behind it. For instance T_{99} values for percentage chlorine reduction were 80 and 230 minutes for containers placed in front and behind the window respectively.

From the batch results it was concluded that some of the important advantages of the halsol technique are the following

- Enhancement of the biocidal action by the combined effects of the free residual halogens, sunlight and the possible involvement of singlet oxygen
- Removal of objectionable tastes and odors produced by high halogen doses
- Possible role of solar radiation in the formation of THM

The reactions of halogens with water as a function of pH and temperature could be complicated by the formation of a variety of species. The formation of chlorine monoxide (ClO_2) for instance as a very reactive species has been postulated to occur at a pH below 8.

$HOCl + HOCl \leftrightarrow ClO_2 + H_2O$

The Mechanism of photodecomposition of the diverse halogen species formed also becomes equally complex, particularly by the potentially different effects of the polychromatic characteristics of sunlight. Nevertheless a first order kinetic reaction for the solar dehalogenation process has been assumed on the basis of an exponential relationship expressed as follows

$C/C_o=e^{-Kit}$ where C_o is the initial halogen residual concentration, K is the photodecomposition rate constant (square centimeters per microwatt minute), I is the incident solar UV-A intensity (microwatts per square centimeter), t is exposure time or photoreaction time

$R=100e^{-KIt}$ where R is the halogen residual remaining (percent)

Results from Batch tests show that

- The reactive species formed in water (HOCl and HOI are sufficiently photosensitive to allow their rather rapid photodegradation
- The photoreaction is capable of occurring in quiescent water exposed to sunlight in transparent glass containers having mean diameters up to 20 cm
- The most effective photoreactive components of sunlight capable of penetrating through the class and the water were those I the wavelength of 310-400 nm with the violet blue light next in order of effectiveness

Appendix B:Trip Report

Duration: January 10 - January 28
Purpose: To investigate the viability of various Point-of-use Disinfection methods for application on a household level.

Jan. 10. Arrive in Kathmandu

Jan. 12. Meet with representatives from UNICEF-Nepal at the Melamchi Water Supply project offices in Kathmandu. We were debriefed as to the current situation on the ground in Nepal and given hints as to what would be the best way of going about our intended research. The representatives from UNICEF seemed very interested in Point-of-use treatment as part of a solution for the public health issues related to polluted water. The point was raised that in addition to any technical recommendation by way of a filter or disinfection device there is a serious need for re-education and awareness raising amongst the rural people of Nepal who are most affected by water borne disease. We arrange to go to the Kavre district on a research/fact-finding trip organised by UNICEF who also want us to give a series of presentations and workshops on our methods and findings

The topic of arsenic is raised and is of concern to all present. We are cautioned to be very careful about any information we might have or gain along the way as a national uproar about arsenic poising is something the authorities want to avoid at all costs. The reasons given for this caution is that Nepal is not capable of dealing with this issue on any level and thus would prefer not to discuss it even if arsenic were prevalent, at least until mechanisms were set in place to deal with the issue. Mr. Sharma of the Department of Water Supply and Sewerage gives a short presentation on what is known so far on arsenic contamination in the Terai and invites Andy and Tricia to go on a field trip with him.

Jan 12-15: Get acquainted with the city, attempt to purchase supplies for the upcoming lab work. Find a surprising dearth in liquid bleach (sodium hypochloride), as I am unable to find it in any store except in a few upscale supermarkets in the tourist district, which have it as a scented luxury item.

Jan 15: Move to staff college with the assistance of Mangala and Dilli Bajracharya. Drop off equipment at Central lab.

Jan. 16: Clean assigned workspace in the central lab and start performing solar disinfection experiments using locally available blue and white plastic bottles. Have brief discussion with Dilli Bajracharya on the relative merits of the various disinfection options, Dilli's recommendations as follows:

1) Chlorine is not readily available in Nepalese retail establishments, as they do not use it for washing or cleaning purposes. Nepalese are also particularly sensitive to chlorine; any chlorination would have to be at the bare minimum residual levels to ensure that the water taste and smell do not change. The tap water in Nepal was

sporadically chlorinated and the water supply autgh horities use Bleaching Powder (Calcium Hypochlorite) that is manufactured in the Terai region.

2) Ultraviolet disinfection is not a viable option since it is expensive and requires electricity which is not readily available
3) Solar disinfection was of great interest to Mr.Bajracharya. He said that it was a traditional Nepalese method of water purification and that his father used to keep his drinking water in a vat on the roof during the day for consumption the following day.

Jan. 17: Work all day at the central lab. Continue with the solar disinfection studies; try to do some chlorination experiments with the bleaching powder provided by Mr. Bajracharya. Have trouble with the bleaching powder that was of uncertain age and of variable chlorine content. Make a stock solution for dosing however had further trouble with excess lime precipitation from the bleaching powder that added turbidity to the solution.

Susan returns from her meeting with the Federation of Business and Professional Women- Nepal and informs us of her conclusions from that discussion. Her conclusions of what was discussed reinforces my suspicion as to the impracticality of chlorination on a household level and the viability of solar disinfection if it were to prove an effective disinfectant in the Nepalese climate. In addition Susan came away from the meeting with the recommendation that we should not offer the village women too many choices as it would confuse them, rather we should give them one "solution" and try to make sure they abided by it. I express my concern with respect to that recommendation. My concern is that westernised urbanised professional women might not have a proper conception on how to deal with rural women due to a cultural gap analogous to that between a westerner and a rural Nepalese.

Jan 18: Work the morning at the Central Lab, continue with the solar and chlorine experiments.

Afternoon go on the field trip to Kavre. Arrive in the evening and get to see a first hand view of what life outside the metropolitan region looks like. The difference between the city and the country side is large even though we are assured that relative to villages further west and east this is a very well to do village, the infrastructure is very minimal. The village houses are without piped water and plumbing, and even for the few houses connected to the power grid, electricity is sporadic. Water for drinking and washing purposes is collected from either from 2 water taps provided by the municipality (piped from a nearby spring source untreated) or from a stream that runs through the village.

Our guide and translator on this trip is an engineer working for the DWSS by the name of Pren Shrestra. He is able to offer us an important insight to the work that we are trying to do in this area. He works as a contact between the DWSS and the local women of the region and organizes workshops and the like to educate them as per proper water handling and sanitation behavior. He provides us with valuable insights into what he believes would and would not work in the field. He shows interest in solar disinfection and repeats Dilli's assertions with respect to chlorine.

Jan 19: Meet with Mr. Shrestra's village "motivators" or contact people in charge of disseminating information supplied to them by the DWSS and UNICEF. We conduct a brief training session with the motivators showing them the various techniques that we were investigating. As with most Nepalese we had met thus far they were not very optimistic about the possibility of chlorinating their water on a household level, and they showed a strong enthusiasm for solar disinfection.

Jan 20: Work at the Central Lab. Begin to do some experiments with half blackened containers and thick glass containers in order to determine whether I could raise the temperature of my waters to achieve some type of heat induced disinfection. The thick glass bottles were similar to jars and were used to study whether glass jars or other similar container could be used.

Jan 21: Nagarkot, project and current research presentation in the DWSS's Central Human Resource Development Unit to a group of local engineers and concerned parties. Demonstrated the particulars of my research, got similar feedback as before, except the scientists and engineers present were even more sceptical than the villagers as to the effectiveness of the process. Made the acquaintance of an engineer by the name of Thakur Pandit, who was interested in conducting his own studies on the matter. Mr.Shrestra demonstrates the Delagua/Oxfam field kit that the DWSS uses to conduct field tests.

Jan 22: Sightseeing and socializing with the engineers and technicians in the CHRDU.

Jan 23-27: Central Lab, experiments concentrating mainly on solar disinfection, getting solar data and disinfection information for the various types of containers.

Jan 28: Depart Kathmandu for Cambridge

Appendix C: The MIT Nepal Water Project

The research upon which this thesis is based was conducted as an integral part of the MIT Nepal Water Project. The objectives of this project are to assess the water quality of selected urban and rural locations in Nepal and to recommend point-of-use (POU) treatment methods to decrease the risk of waterborne illnesses. Seven Master of Engineering students from Massachusetts Institute of Technology (MIT) and advisor Susan Murcott spent three weeks in Nepal in January 2000 collecting and analyzing samples, evaluating water treatment methods, and investigating the water supply in Nepal. The water quality team focused on microbial, arsenic, and nitrate and ammonia contamination of drinking water. Coagulation, filtration, and disinfection, were studied for adaptation to a point-of-use application.

BIBLIOGRAPHY

Acra, A., Jurdi, M., Mu'allem, H., Karahagopian, Y. and Raffoul, Z., Water Disinfection by Solar Radiation: Assessment and Application, (Ottawa, Ontario, Canada: International Development Research Centre, 1990)

Acra, A., Raffoul, Z., Karahagopian, Y., Solar Disinfection of Drinking Water and Oral Rehydration Solutions, (Paris: UNICEF. 1984)

Adhikari A., "Environmental Problems in the Kathmandu Valley," in Urban and Environmental Planning in Nepal. IUCN The World Conservation Union, 1998

Ahmed I., Dixit A, and Nandy A., "Water, Power and People: A South Asian Manifesto on the Politics and Knowledge of Water," in Water Nepal, Vol. 7, No. 1, Jan-Aug 1999, pp. 113-121.
Bagmati River. MIT Masters Thesis, Cambridge MA, 2000

Andreatta D, Yegian DT, Connelly L, and Metcalf RH., "Recent Advances In Devices For The Heat Pasteurization Of Drinking Water In The Developing World" in Proceedings of the 29th Intersociety Energy Conversion Engineering Conference, American Institute of Aeronautics and Astronautics, Inc., 1994.

Bittner AB., Nepal Drinking Water Quality Assessment: Nitrates and Ammonia, Massachusetts Institute of Technology Masters Thesis, Cambridge MA, 2000

Blumthaler M, Ambach W, Huber M., "Altitude Effect of Solar UV Radiation on Albedo, Turbidity, and Solar Elevation", in Meteorologishe Zeitschrift, Vol 2 No. 3 1993: pp. 116-120

Bottino A, Thapa A, Scatolini A, Ferino B, Sharma S, Pradhananga TM., "Pollution in the Water Supply of Kathmandu City", Draft Article Submitted to the Journal of the Nepal Chemical Society, 1991

Brooks DB., "Water Demand Management: Conceptual Framework and Policy Implementation," in Water Nepal, Vol. 7, No. 1, Jan-Aug 1999, pp. 9-17.

Conroy RM, Elmore-Meegan M, Joyce T, McGuigan KG, Barnes J., "Solar disinfection of drinking water and diarrhoea in Maasai children: a controlled field trial," Lancet. 1996 Dec 21-28; 348 (9043), pp. 1695-7.

Culp GL, Culp RL., New Concepts in Water Purification, (New York, NY: Litton Educational Publishing, Inc., 1974)

EAWAG/SANDEC, SODIS News No. 3, August 1998, http://www.sodis.ch

EAWAG/SANDEC, SODIS News No. 4, May 1999, http://www.sodis.ch

Federal Emergency Management Agency (FEMA), Are You Ready? Your Guide to Disaster Preparedness (H-34) Item #8-0908, http://www.fema.gov/

Federal Emergency Management Agency (FEMA), Emergency Preparedness Checklist (L-154) Item #8-0872, http://www.fema.gov/

Federal Emergency Management Agency (FEMA), Emergency Preparedness Publications (L-164) Item #8-0822, http://www.fema.gov/

Federal Emergency Management Agency (FEMA), Your Family Disaster Plan (L-191) Item #8-0954, http://www.fema.gov/

Federal Emergency Management Agency (FEMA),Your Family Disaster Supplies Kit (L-189) Item #8-0941, http://www.fema.gov/

Iqbal, M., An Introduction to Solar Radiation, (New York, NY, Academic Press Inc, 1983)

Joyce TM, McGuigan KG, Elmore-Meegan M, Conroy RM "Inactivation of fecal bacteria in drinking water by solar heating." Appl Environ Microbiol. 1996 Feb;62(2):399-402.

Karmacharya AP, Shrestha RK, Shakya S., Monitoring of the Kathmandu City Water Supply with reference to Chlorination and Microbiological Quality 1991/92, (Kathmandu: Environment and Public Health Organization, 1992)

Landsberg HE, Lipman H, Paffen K and Troll C., World Maps of Climatology (Berlin, Germany: Springer-Verlag New York, Inc. 1965)

Lehr JH, Gass TE, Pettyjohn WA, DeMarre J., Domestic Water Treatment, (New York, NY: McGraw-Hill, 1980)

Lucas BD., "Sunburn risk increases with altitude", in Patient Care Vol. 33 1999: pp. 18-20

Mancl KM., "Bacteria in Drinking Water." in Ohio State University Extension Bulletin 795, 1989, http://ohioline.ag.ohio-state.edu/b795/

Mani A, Randgarajan S., Solar Radiation over India, (New Delhi, India: Allied Publishers Private Limited, 1982)

Mani A.,Handbook of Solar Radiation Data for India, (New Delhi, India: Allied Publishers Private Limited, 1980)

McGuigan KG, Joyce TM, Conroy RM, Gillespie JB, Elmore-Meegan M., "Solar disinfection of drinking water contained in transparent plastic bottles: characterizing the bacterial inactivation process," J Appl Microbiol. 1998 Jun; 84 (6): pp. 1138-48.

McGuigan KG, Joyce TM, Conroy RM., "Solar disinfection: use of sunlight to decontaminate drinking water in developing countries," J Med Microbiol. 1999 Sep; 48(9): pp. 785-7.

Mendis D.L.O., "Hydraulic Engineering Versus Water and Soil Conservation Ecosystems: Lessons From the History of the Rise and Fall of Sri Lanka's Ancient Irrigation Systems," in Water Nepal, Vol. 7, No. 1, Jan-Aug 1999, pp. 49-89.

Moench, M, Caspari E, and Dixit A. eds., Rethinking the Mosaic: Investigations into Local Water Management, (Patan Dhoka, Nepal: Jagadamba Press, 1999)

Moulton P, "Proposal for a Pilot Clean Water Project in Nepal", Global Resources Institute

Moulton P, "Water Survey and Testing", Global Resources Institute

Nepal Environmental & Scientific Services (NESS) Private Limited http://www.southasia.com/environment/

Nepal Ministry of Home Affairs, http://www.south-asia.com/hmg_home/

NFSD: University of Florida Disaster Handbook Guide, http://www.agen.ufl.edu/~foodsaf/he117.html

Reed, RH. "Solar Inactivation of Faecal Bacteria in Water: The critical role of Oxygen," in Lett Appl Microbiol. 1997 Apr; 24(4), pp. 276-80

Rijal GK, Fujioka RS., “Disinfecton of water using solar and ultraviolet technologies.” in Water Resources Research Center Conference Proceedings: Appropriate technologies and issues for water resource management on tropical islands in the Asia/Pacific region. June 1996

Rijal GK, Fujioka RS and Ziel C., “Assessing the Microbial Quality of Drinking Water Sources in Kathmandu, Nepal”

Sagara J., Study of Filtration for Point-of-use Drinking Water Treatment in Nepal, Massachusetts Institute of Technology Masters Thesis, Cambridge MA, 2000

Shrestha, MN, “Melamchi: Pipe Dream in the Pipe Line”, Nepal Water Supply Corporation: www.panasia.org.sg/nepalnet/water/melamchi.htm

Shrestha, N., In the Name of Development, (Kathmandu, Nepal: Educational Enterprises (P) ltd., 1997)

Shrestha RR, Sharma S., Bacteriological Quality of Drinking Water in Kathmandu City: A Review of ENPHO/DISVI Reports, 1988-1992, (Kathmandu: Environment and Public Health Organization, 1995)

Shultz CR, Okun DA., Surface Water Treatment for Communities in Developing Countries., (New York: John Wiley and Sons, 1984)

Sommer, B., *et al.* “SODIS - an Emerging Water Treatment Process,” J. Water SRT-Aqua, 46, No. 3, 1997, pp. 127-137.

Tech Brief (June 1996), A National Drinking Water Clearinghouse Fact Sheet (http://www.estd.wvu.edu/ndwc/NDWC_homepage.html)

UNDP, Nepal Human Development Report 1998. (New York: United Nations Development Program, 1998)

Viessman W, and Hammer M., Water Supply and Pollution Control – 6th ed., (Menlo Park, CA: Addison Wesley Longman, Inc., 1996)

Water Review Technical Brief, Volume 6, No.1; A publication of the Water Quality Research Council, 1991

Wegelin, M., Canonica, S., Mechsner, K., Pesaro, F. and Metzler, A., . “Solar Water Disinfection: Scope of the process and analysis of radiation experiments,” J. Water SRT-Aqua, 43, No. 3, 1994, pp. 154-169.

Whittington D, and Swarna V., The Economic Benefits of Potable Water Supply Projects to Households in Developing Countries, Economic Staff Paper Number 53, (Manila: Asian Development Bank 1994)

Wolfe A., Microbial Contamination of the Kathmandu Valley Drinking Water Supply and Bagmati River, Massachusetts Institute of Technology Masters Thesis, Cambridge MA, 2000