SOLAR DISINFECTION FOR POINT OF USE WATER TREATMENT IN HAITI

by

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Submitted to the Department of Civil and Environmental Engineering on May 11th, 2001 in partial fulfillment of the requirements for the degree of Master of Engineering in Civil and Environmental Engineering.

ABSTRACT

Haiti is the poorest nation in the western hemisphere and cannot afford conventional means of water treatment. Consequently, waterborne disease causes great suffering and death throughout the Haitian community. This research effort investigates using solar disinfection or SODIS for point-of-use water treatment in Haiti, which can provide disease-free water at the cost of a plastic bottle. The SODIS treatment process consists of filling plastic bottles with water and exposing them to sunlight. SODIS operates on the principle that sunlight-induced DNA alteration, photo-oxidative destruction, and thermal effects will inactivate microorganisms. To achieve adequate disinfection, an area should receive at least 500 W/m^2 of radiation for 5 hours. Haiti and other developing countries do not have sufficient meteorological data to assess if they meet this threshold. A mathematical model is presented, calibrated, and used to simulate monthly average, minimum, and maximum daily sunlight intensity profiles to estimate if Haiti would be suitable for SODIS. This method is general in that it can be used to simulate sunshine intensity profiles anywhere in the world per degree longitude and latitude. The sunshine simulations suggest that SODIS would be applicable throughout Haiti year-round. Field studies were conducted in Haiti during January 2001 to test SODIS. SODIS efficacy was evaluated by the inactivation of total coliform, *E. coli*, and H_2S-producing bacteria under different natural conditions. Exposure period proved critical. Under various sunshine intensities, bottle water temperatures, and initial bacterial amounts, 1-day exposure achieved complete bacterial inactivation 52 % of the time, while the 2-day exposure period achieved 100 % microbial inactivation for every test. To maintain the beauty of this technology, a practical way of providing people with cold water every morning that has undergone a 2-day exposure period has been developed and termed a “SODIS triangle.” Essentially, it consists of three groups of bottles that are rotated every morning, so two groups are out in the sun and one is being used for consumption. It is hoped that this relatively new disinfection method will provide an economically feasible technology to improve water quality and public health in Haiti.

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DEDICATED TO MY PARENTS PETER AND NANCY
TO WHOM I OWE EVERYTHING

TO MY SISTER KATE FOR NOT LETTING ME BE COMPLETELY ENGULFED BY SCIENCE

TO WLBC AND THE LATE NIGHTS OF PHILOSPHY THAT HELPED PUT ME HERE

A HEARTFELT THANK YOU TO MY TEAMATES AND FRIENDS
NADINE, DANIELE, AND FARZANA
AND MY ADVISORS
PETER SHANAHAN AND MARTIN POLZ

A MOST SINCERE THANK YOU TO THOSE WHO MADE THIS EXPERIENCE POSSIBLE
SUSAN MURCOTT; PHIL, BILL, TRUDI, AND KEVIN FROM GIFT OF WATER; AND NATHAN AND WANDA FOR THEIR HOSPITATLIY

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1 Introduction

Water is the most ubiquitous compound in living cells and it is imperative to all forms of life. Haiti is the poorest nation in the western hemisphere and potentially faces catastrophe from lack of this essential resource. Pastor Nathan Dieudonne, an outstanding member of the Haitian community, commented on the current water situation in Haiti during a recent interview for the Bethel Missions Church:

Interviewer: *"What about the water in Haiti? Is the water safe to drink for the general public?"*

Pastor Nathan: *"Bad water is [the] number one problem we have in Haiti. [In] Haiti we don't have good water anywhere, even in the city. There is no good water."*

Interviewer: *"Would you say then that's probably one of the main reasons for a lot of the sickness and death in Haiti, because of the water?"*

Pastor Nathan: "*Yes, exactly"*
(Bethel Missions of Haiti Vision 2000 New Medical Clinic, 2000)

Overpopulated, Haiti's resources are exhausted and trends of further deterioration are readily apparent. Vast advancements in water resources are needed to improve the livelihood for the warm and wonderful people of Haiti.

Haiti occupies the second largest island in the Caribbean at 18° to 20° N and 71° 45' to 74° 34'W. It is located in the western third of Hispaniola surrounded by the Atlantic Sea to the north, the Caribbean Sea to the west and south, and the Dominican Republic to the east (Figure 1-1).

Figure 1-1. Map of Haiti

Haitians are of approximately 95% African decent and some still practice traditional voodoo despite the state religion of Catholicism. French is the official language, but 80% of the population speaks Creole. In 1994, the United States forcibly tried to reinstate democratically elected president Jean-Bertand Aristide who was removed by the army in 1991. Eventually, the U.S. forces were replaced by a U.N. military mission. The external fighting and internal struggle for power amongst Aristide's successors has created chaos. This has left Haiti without a functioning government since June 1997 and deprived the country of 150 million dollars in foreign aid (Country Profile: Haiti., 2000). The resulting

turmoil has adversely impacted Haiti's public health, particularly water related issues. Haitian water is the focus of this study and will now be discussed in more detail.

1.1 Haitian Water Resources

Water in Haiti is generally available from precipitation, rivers and surface water, and groundwater. All of these resources are intimately related in the hydrologic cycle, which ultimately provides water for the Haitian community. The amount of water potentially available from each resource will now be examined followed by the impacts of deforestation.

1.1.1 Precipitation

Most precipitation is brought by the northeast trade winds with a slight contribution from easterly winds. Extreme patterns including storms, hurricanes, droughts, and floods are common. Rainfall can range from less than 30 mm in the northwest to more than 3000 mm in the mountains of the southwest. Orographic factors greatly influence site-specific rainfall patterns creating the largest precipitation amounts in highly mountainous areas (USAID, 1985). A rough characterization of rainfall for seven principal areas in Haiti is (Library of Congress, 1979):

- Northern plain and mountains: More than 1270 mm, with as much as 2540 mm on the higher mountains.
- Northwest: Semi-arid conditions prevail throughout the region, especially around Mole St. Nicolas (508 mm) on the extreme western end of the northern peninsula; Port-de-Paix has about 1524 mm in the mountainous areas.
- Western coast from Mole St. Nicolas to the Cul-de-Sac Plain at Port-au-Prince: Very dry with 500 to 1000 mm of rain; a semi-arid area extending back from the coast over the plain to the mountains covered xerophytic vegetation.
- The island of La Gonave: Similar cover and a rainfall of about 508 to 762 mm.

- Artibonite Valley: Lower portion of the valley is a semi-arid region, but rainfall increases rapidly up the valley until it reaches a mean annual level of about 3000 mm; however, about 40 km away in the Cul-de-Sac plain, at about the same altitude, the driest area receives about 500 to 750 mm.
- Eastern part of the mainland between the two peninsulas: The Central Plateau receives about 1016 to 1524 mm of rain.
- Southern Peninsula: Well-watered, with 1524 mm of rain or more in all parts, except the southern slope of the western and a small area near Anse-a-Pitre in the Southeast.

The amount of rainfall that does not infiltrate the ground becomes present in the form of rivers and surface water.

1.1.2 Rivers and Surface Water

Surface water is used by the majority of Haitians. Most of Haiti's rivers are short and swiftly flowing with the exception of the Artibonite River. The broken and steep landscape gives rise to numerous streams and rivers. However, most of these rivers only flow during periods of rainfall and few rivers have permanent flow (USAID, 1985). The principal rivers and corresponding catchment area size are provided by Table 1-1:

Table 1-1. Principal Catchment Areas of Haiti (Library of Congress, 1979)

Main River	Average Runoff [m^3/s]	Length [km]	Catchment Area [km^2]
Aribonite	34	280	6,862
Riviere de la Grande-Anse	27	90	556
Riviere de l'Estere	19	NA	834
Les Trois Rivieres	12	102	897
Riviere de Cavillon	9	43	380
Grande Riviere du Nord	7	70	312
Riviere du Limbe	6.4	70	312
Riviere Momance	6.4	53	330
Grande Ravine du Sud	3.9	34	330
Grand Riviere du Cul-de-Sac	3.3	NA	290
Riviere l'Acul	NA	36	NA

Although these flows are presented as averages, they are still highly irregular. The amount of precipitation that does not contribute to surface water percolates into the soil and is available as groundwater.

1.1.3 Groundwater

Groundwater is Haiti's second most important water resource and could become the primary supply of freshwater in the future. Limestone underlies 80% of the nation making groundwater readily accessible with well-drilling equipment. Water quality is high, although hard and slightly saline in some cases. Groundwater is especially abundant in the coastal plains and these aquifers can yield between 10 to 120 liters a second. Port-au-Prince and domestic areas such as Cul-de-Sac, Leogane, Carrefour, St-Marc, Cabaret, Grande-Riviere Du Nord, Limonade, Ouanaminthe, and Aquin widely use groundwater for domestic purposes (Library of Congress, 1979). Some regions of Haiti contain ample groundwater but they could be hard to develop as they contain a karstic substratum (USAID, 1985). HARZA (1979) estimated the potential groundwater resources in 22 select areas summarized by Table 1-2.

Table 1-2. Groundwater Potentials for 22 selected areas (HARZA, 1979)

Region	Number of Project Areas	Number of Project Aquifers	No. of Aquifers	Water flow [l/s]
North and North Western	7	13	7	500-685
Artibonite	2	2	-	-
Southeast Coast	3	5	2	399-1114
South Coast	5	3	2	530+
Central Plains	5	6	1	15-45
Total	22	29	12	1444-1844

The onset of any future development of this resource must be carefully evaluated. If pumping rates exceed groundwater recharge rates, salinization of the freshwater could occur. Additionally, to obtain optimal benefits from groundwater, as well as surface water, the effects of deforestation must not only be considered but also remedied.

1.1.4 Impacts of Deforestation

Groundwater and surface water resources depend on the capacity of a watershed to store water and then gradually release it into rivers and recharge water tables. The ability of a watershed to retain water depends on its vegetative properties. Surface root structures, small plants, and dead leaf matter increase overland friction to flow and this allows more surface water to infiltrate. Deforestation causes a much larger portion of the water to flow overland, which decreases groundwater base flow. This causes river levels to rise and fall dramatically as a function of precipitation events. This type of river flow provides a highly variable and ultimately unreliable source of water. Additionally, loss of vegetative cover results in significant soil erosion, which degrades both upland and downstream areas and causing high maintenance costs.

At the beginning of the 16th century, Haiti was covered with lush forests. As of today, only about 7% of the land is forested. Twelve of the thirty major watersheds were deforested by 1978. If the rate of deforestation continues, only one pine forest and its corresponding watershed will remain by the year 2008 (USAID, 1985). The effect of little vegetative cover on Haiti's River flows can be seen in Table 1-3.

Table 1-3. Deforestation and River Discharges (OAS, 1972; HARZA, 1979; Sheladia Associates, 1983)

River	Site of Cleared Land	Year [1900]	Mean [m^3/s]	Max [m^3/s]	Min [m^3/s]
Trois	Paulin Lacorne	65-67	13.13	527.0	2.65
	Pont Gros Morne	23-40; 62-47	6.95	1,500.0	.3
	Plaisance	25-40; 62-67	.87	193.0	.01
Limbe	Roche a l'Inde	22-40	4.29	458.0	.3
Grande River du Nord	Pont Parois	22-40	3.41	9.4	-
Massacre	Ouanaminthe	22-40	5.34	450.0	.05
Boyaha	St. Raphael	22-40	3.41	9.4	-
Guayamouc	Hinche	26-31	25.52	900.0	.9
Artibonite	Mirebalais	22-40	86.9	2,500.0	8.4
Artibonite	Pont Sonde	22-40	101.4	850.0	11.1
Estere	Pont Estere	65-67	18.76	95.3	1.85
Fer-a-Cheval	Pont Petion	23-31	11.85	700.0	.73
Blanche	La Gorge	22-40	1.97	200.0	.65
Grise	Amt. Bassin Gen.	19-40	3.97	475.0	.31
Pedernales	Anse-a-Pitre	29-30	.46	.8	.06
Marigot	Peredot	28-30	2.42	79.0	.07
De Jacmel	Jacmel	26-31	4.67	800.0	.12
Momance	Amont Barrage	20-40	5.88	420.0	.6
Cotes de Fer	Cotes de Fer	28-30	.27	7.5.0	0.0
Cavaillon	Cavaillon	22-41	9.42	1,035.0	.70
Islet	Charpentier	23-31	2.52	500.0	.66
Torbec	Torbec	23-31	2.66	188.0	.39
Ravine du Sud	Camp Perrin	23-35	4.88	350.0	.28
Grande Anse	Passe Ranja	25-31	26.85	60.0	.70
Voldrogue	Passe Laraque	28-30	6.07	-	.52
Limbe	Pont Christophe	22-30	7.1	-	.3
Gallois	Grison Garde	22-31	.44	-	0.0
Estere	Pont Benoit	22-31	3.95	-	0.0
Bois	Verrettes	24-31; 33-40	2.58	-	.8
La Theme	Passe Fine	23-31	4.76	-	.64
Montrouis	Pont Toussaint	24-30	1.84	-	.15
Torcelle	Messaye	22-41	1.15	-	0.0
Courjol	Bassin Proby	22-39	1.23	-	.3
Matheux	Arcahaie	22-36	1.50	-	.4
Islet	Cayes	23-31	2.68	-	.64
Acul	Carr. Valere	83	3.7	-	-

There is a 99% average difference between maximum and minimum flow for this data, which means there are extreme periods of plentiful and deficient water. The goal is to have a steady source of water available, which may not be possible with the current amount of deforestation. Significant actions need to be taken to protect and restore the vegetative cover, and thus the water resources of Haiti's watersheds. Although Haiti's water resources are not known in detail, with the right care, they are believed to be adequate to meet the needs of the Haitian people. One major task is harnessing these resources and delivering them to the Haitian people.

1.2 Haitian Water Supply

Two government sections are responsible for managing and developing water resources in Haiti. The Ministry of Agriculture, through the Services des Ressources en Eau, is in charge of water resources studies, research, control, and protection. The Ministry of Public Works provides drinking water through two organizations: Centrale Autonome Metropolitaine d'Eau Potable (CAMEP) for the metropolitan area, and Service Nationale d'Eau Potable (SNEP) for the remainder of the country. In reality, there is little control over the use of water resources and several other government and non-government organizations administer water supply programs (USAID, 1985).

In 1978, there were 40 domestic water supply systems in the country serving 700,000 people, or roughly 15 percent of the population (HARZA, 1979). The existing water supply programs are the result of investments by government agencies, and bilateral and multilateral cooperation organizations. In 1984, the government devoted 4 percent of the

budget to potable water projects and this contribution was financed at 84 percent by external assistance (USAID, 1984).

CAMEP serves Port-au-Prince, Petionville, Carrefour, and Delmas. CAMEP supplies its customers from 17 springs and 3 wells from the Cul-de-Sac (USAID, 1985). The upkeep of these structures and associated distribution pipes leave much to be desired. Water loss from the pipes is estimated from between 50 and 70 percent (DATPE, 1984; Fass, 1982). All of these sources, with the exception of Doco Spring, have disinfection units but they are usually not operational. CAMEP nominally serves about 500,000 people through 40,000 connections and 80 functioning standpipes. In actuality, only about 80,000 people utilize CAMEP as their legal source of water. Approximately 300,000 people obtain water from private vendors, 100,000 share a connection with a subscriber, and about 40,000 illegally tap into CAMEP's pipes (USAID, 1985).

SNEP is responsible for the construction, operation, and maintenance of all water supply systems outside the metropolitan area. SNEP's finances are severely limited it but has received assistance from UNICEF, WHO, The World Bank, Inter American Development Bank, German Foundation for Technical Assistance, and USAID (USAID, 1985). SNEP has 185 water supply systems in operation, serving a total population of 700,000. Most of these systems are capped springs. Community systems range from a dug or bored well with a hand pump serving about 200 people, to house connections and public fountains that serve about 60,000 (USAID, 1985). Several organizations helped finance or physically participated in the construction of these systems: IDB, Organization

pour le Development du Nord, and Department de la Sante Publique et de la Population at the Ministry of Health. In addition, several non-governmental organizations made vital contributions: CARE, World Church Service, Missionary Church Association, German Foundation for Technical Assistance, and Canadian Agency for International Development. A summary of water supply systems is given by Table 1-4.

Table 1-4. Water Supply Systems (HARZA, 1979; USAID, 1985)

Service Area	1978	1985	1991
Metropolitan Area	460,000	500,000	600,000
Balance of West Department	60,000	150,000	290,000
Southeast Department	14,600	30,000	80,000
North Department	30,900	150,000	290,000
Northeast Department	5,400	15,000	90,000
Artibonite Department	51,000	160,000	360,000
Center Department	17,500	30,000	80,000
Northwest Department	36,300	40,000	130,000
South Department	24,000	75,000	230,000
Grand' Anse Department	14,900	50,000	150,000
Total Served	715,000	1,200,00	2,300,000
Total Population	4,750,000	5,200,000	5,600,000
Percent Served	15%	23%	41%

1985 Systems under POCHEP and UNICEF			
Service Area	**Population Served**	**Service Area**	**Population Served**
North (18)	15,200	West (50)	27,400
Northeast (0)	0	Southwest (3)	4,900
Artibonite (38)	34,100	South (18)	23,100
Center (4)	6,500	Grande Anse (8)	9,500
Northwest (0)	0	**Subtotal (139)**	120,700

A major problem with these water supply systems is there is no presence of national drinking water supply standards. The managers of CAMEP, SNEP, Public Hygiene Division, and Sanitation Office indicate the main concern is bacteriological

contamination. It is generally agreed that there is enough water for drinking purposes and the real issue is to develop the quality of the resource (DATPE, 1984).

1.3 Haitian Water Quality

Water-related diseases run rampant in Haiti. CAMEP and SNEP water is theoretically disinfected before distribution. However, treatment is very erratic due to breakdowns and lack of backup supplies. Surface water and groundwater from uncapped springs is considered unsafe due to the high risk of contamination. Water from private vendors can pose a risk of disease because it is not disinfected and the sources are unprotected. Even bottled water cannot be guaranteed, as there is potential contamination during the shipping process. Essentially, there is no controlled potable water in Haiti and every source could contain pathogens (DATPE, 1984).

Waterborne pathogens are capable of causing illness depending on the dose and physical condition of the exposed individual. Infectious organisms found in water may be discharged by human beings who are carriers of a disease. Pathogenic organisms include bacteria, viruses, protozoa, and helminthes, which can all cause a wide array of diseases. Table 1-5 depicts common perilous organisms found in water and their corresponding disease.

Table 1-5. Infectious Agents Present in Raw Domestic Wastewater (Metcalf & Eddy, 1991)

Organism	Disease	Remarks
Bacteria		
Escherichia coli	Gastroenteritis	Diarrhea
Legionella pneumophila	Legionellosis	Acute respiratory illness
Leptospira	Leptospirosis	Jaundice, fever (Weil's disease)
Salmonella typhi	Typhoid fever	High fever, diarrhea, ulceration
Salmonella	Salmonellosis	Food poisoning
Shigella	Shigellosis	Bacillary Dysentery
Vibrio cholerae	Cholera	Extremely heavy diarrhea, dehydration
Yersinia enterolitica	Yersinosis	Diarrhea
Viruses		
Adenovirus (31 types)	Respiratory disease	
Enteroviruses (67 types)	Gastroenteritis, heart anomalies, meningitis	
Hepatitis A	Infectious hepatitis	Jaundice, fever
Norwalk agent	Gastroenteritis	Vomiting
Reovirus	Gastroenteritis	
Rotavirus	Gastroenteritis	
Protozoa		
Balantidium coli	Balanticliasis	Diarrhea, dysentery
Cryptosporidium	Cryptosporidiosis	Diarrhea
Entamoeba histolytica	Amebiasis (amoebic dysentery)	Prolonged diarrhea with bleeding, abscesses of the liver and small intestine
Giardia lamblia	Giardiasis	Mild to severe diarrhea, nausea, indigestion
Helminths		
Ascaris lumbricoides	Ascariasis	Roundworm infestation
Enterobius vericularis	Enterobiasis	Pinworm
Fasciola hepatica	Fascioliasis	Sheep liver fluke
Hymenolepis nana	Hymenolepiasis	Dwarf tapeworm
Taenia saginata	Taeniasis	Beef tapeworm
Taenia solium	Taeniasis	Pork tapeworm
Trichuris trichiura	Trichuriasis	Whipworm

These infectious organisms can have highly deleterious impacts on community members. Table 1-6 shows there were several thousand cases of water related diseases reported in 1980 (CONADEPA, 1984).

Table 1-6. Some Reported Cases of Water Related Diseases in 1980 (CONADEPA, 1984)

Area	Population	Diarrhea		Intestinal Infections		Typhoid	
		Cases	/1000	Cases	/1000	Cases	/1000
Port-au-Prince	650,000	6608	10.2	4694	7.2	460	.7
Gonaives	33,000	225	7.7	167	5.1	11	.3
Port-de-Paix	15,000	455	30.3	2171	145	114	7.6
Hinche	10,000	694	69.4	738	74	100	10.0
St. Marc	23,000	851	37.0	314	13.7	266	11.6
Petit Goave	7,000	294	42.0	1357	194	2	.3
Belladere	2,500	875	350.0	272	109	68	27.2
Jacmel	13,000	320	24.6	152	11.7	87	6.7
North Dept.	560,000	3145	5.6	6819	12.2	141	.3
South Dept.	500,000	1909	3.8	2380	4.8	462	.9

The actual numbers of diarrhea and intestinal infections are much higher as many occurrences are never reported. In 1979, diarrhea alone caused the death of 9% of the babies less than one year of age (USAID, 1984). A study from 1994 to 1995 found nearly one-half of all deaths occurred within the first five years of life. Additional statistics indicate, approximately 74 out of 1,000 births die before one year of age and 131 never reach five years of age (PAHO, 1999). The National Health Survey conducted a survey from 1987-1994 and found that the incidence of diarrhea was about 47.7% in 6-to-11-month-old infants. Diarrheal diseases are the leading cause of illness and death in children under five years of age, and are often associated with malnutrition and acute respiratory infections (PAHO, 1999). These daunting statistics make water quality the biggest water resource issue in Haiti. If correctly managed, there is an ample amount of

water to meet the needs of the Haitians but they need an easy and economical way to destroy waterborne pathogens.

1.4 Point-of-Use Water Treatment

In developed countries, pathogens are typically destroyed by elaborate centralized water treatment plants. Unfortunately, it is not financially possible to upgrade to conventional water treatment technologies in Haiti. As a more plausible alternative, low-cost point-of-use disinfection technologies can treat water and are more economically realistic. The choice of a point-of-use water technique should fulfill the following criteria (Lehr *et al.*, 1980; Shultz *et al.*, 1984):

1. Effective on many types and large numbers of pathogens
2. Should perform regardless of water fluctuations
3. Must operate in appropriate pH and temperature range
4. Should not make the water toxic or unpalatable
5. Should be safe and easy to handle
6. Any chemical concentrations should be minor
7. Must provide residual protection against possible recontamination
8. Units must be affordable to all
9. Should be adaptable to local conditions and variations
10. Specialized equipment should be produced locally
11. Must be accepted by local traditions, customs, and cultural standards
12. Must comply with national sanitation and pollution policies

Common point-of-use disinfection techniques such as chlorination, boiling, and filtration can be successful but have associated problems. Chlorine is the most widespread disinfection method and will be discussed in the most detail.

Chlorine's most important attributes are its germicidal potency and persistence in water distribution systems. Chlorination uses chlorine gas, Cl_2; sodium hypochlorite, *NaOCl*; or

calcium hypochlorite, $Ca(OCl)_2$. These forms of chlorine act as powerful oxidizing agents that damage vital cell structures. The key reaction of the dissolution of chlorine gas in water is as follows:

$$Cl_2 + H_2O \rightleftharpoons HOCl + H^+ + Cl^-$$

$$HOCl \rightleftharpoons H^+ + OCl^-$$

The hypochlorous acid formed, *HOCl*, is the prime disinfection agent. The protonation of hypochlorous acid depends on pH and yields the less effective hypochlorite, OCl^-. Together the *HOCl* and OCl^- make up the free available chlorine, which is most useful for disinfection. In addition, chlorine based compounds can form long lasting residual compounds to provide continual disinfection (Metcalf and Eddy, 1991).

Chlorination has been controversial for decades, as consumers do not like the associated odor and taste. Chlorine also reacts with natural aquatic substances to produce disinfection byproducts such as trihalomethanes (Gibbons and Laha, 1999). Animal and epidemiological studies suggest these byproducts can cause adverse health affects, are possibly carcinogenic, and are linked to an increased risk of birth defects (Trussell 1999; Per Magnus *et al.*, 1999). Furthermore, chlorine poses additional problems such as reliable supply, timely distribution, and correct dosage (Wegelin *et al.*, 1994).

Other household disinfection mechanisms include boiling the water and filtering. In Haiti, boiling water uses energy in the form of firewood, which is no longer possible due to extensive deforestation. Filtration is often unaffordable and is subject to frequent

clogging and leaking. In addition, filtering typically requires additional disinfection steps. These problems call for the development of an alternative disinfection technology that is effective, practical, and simple enough to be applied by individuals at the household level. Under the right conditions, solar water disinfection, or SODIS, may be that alternative.

Section II: SODIS for Point of Use Water Treatment

2 SODIS: Solar Water Disinfection

2.1 SODIS Introduction and Development

SODIS uses the sun's energy to provide an economically feasible means of providing safe drinking water. This treatment process produces disease-free water by filling transparent containers and exposing them to sunlight:

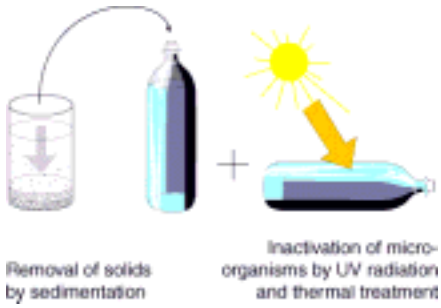


Figure 2-1. SODIS Overview

The science behind SODIS will be discussed after a little background. This technology was pioneered in the late 1970s by Acra *et al.* at the American University of Beirut, Lebanon, to find an inexpensive disinfection method for oral rehydration solutions (Acra *et al.*, 1984). Their exciting results gave birth to a new disinfection technique.

Consequently, a workshop on SODIS was held in Montreal in 1988 (Lawand *et al.*, 1988), and SANDEC/EAWAG (Swiss Federal Institute for Environmental Science and Technology) started to investigate the SODIS process in 1991. Their findings were encouraging and field-tests where launched to include several countries: Columbia, Bolivia, Burkina Faso, Togo, Indonesia, Thailand, and China (EAWAG/SANDEC, 1998). The most alluring aspect of this technology is the low investment costs of plastic bottles and the disinfection energy that is provided free of charge by the sun.

2.2 Solar Radiation and Disinfection

SODIS uses the destructive power of different bands of the electromagnetic spectrum to destroy pathogens. Photodynamic inactivation of microorganisms was first demonstrated by Raab in 1900. The sun emits energy in the form of electromagnetic radiation that covers the ultraviolet, visible, and infrared range. The most important bandwidths for SODIS are the UV-A, red, and infrared, which are shown in relation to the electromagnet spectrum by Figure 2-2.

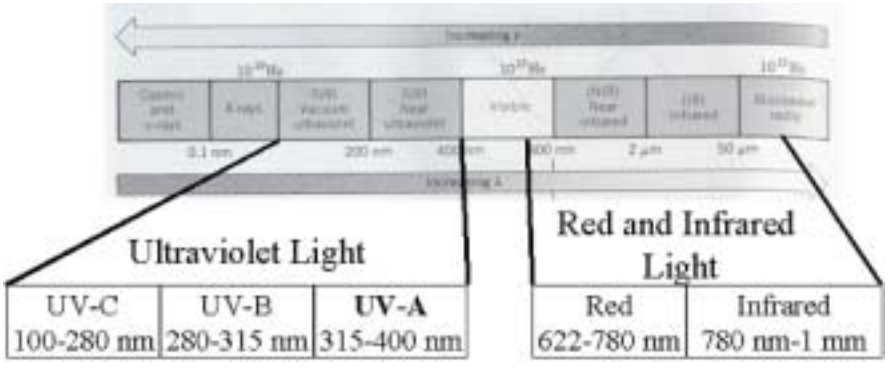


Figure 2-2. Important Components of the Electromagnetic Spectrum (Solomon, 1996)

Recent studies have shown that UV-A light is the main bandwidth involved in the eradication of microorganisms (Acra *et al,* 1984; Acra *et al.,* 1990; Reed *et al.,* 1997; McGuigan *et al.,* 1998). UV-A has direct effects on DNA and forms highly destructive oxygen species as a secondary product. In addition, water strongly absorbs red and infrared light creating heat, which results in pasteurization. Figure 2-3 shows the combined effects of UV-A and water temperature on coliform bacteria.

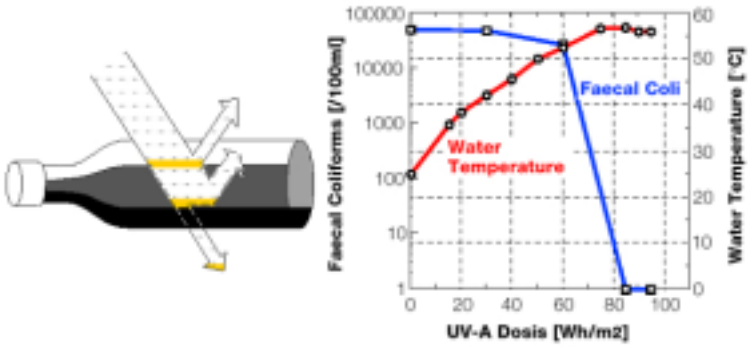


Figure 2-3. UV-A and Temperature Effect on Fecal Coliform (EAWAG/SANDEC, Technical Notes).

Microbial inactivation is contingent on the disinfection mechanisms of DNA alteration, photo-oxidative destruction, and thermal pasteurization damaging cellular defenses. This concept for each process will now be discussed further.

2.3 DNA Alteration by UV

To assure pathogenic organisms are eradicated, DNA must be damaged faster than microbes can repair it. DNA has a maximum UV absorbance at around 260 nm that causes mutagenesis and results in cellular death (Raven and Johnson, 1996). Absorbed UV light causes adjacent thymine bases to covalently bond together, forming thymine dimers:

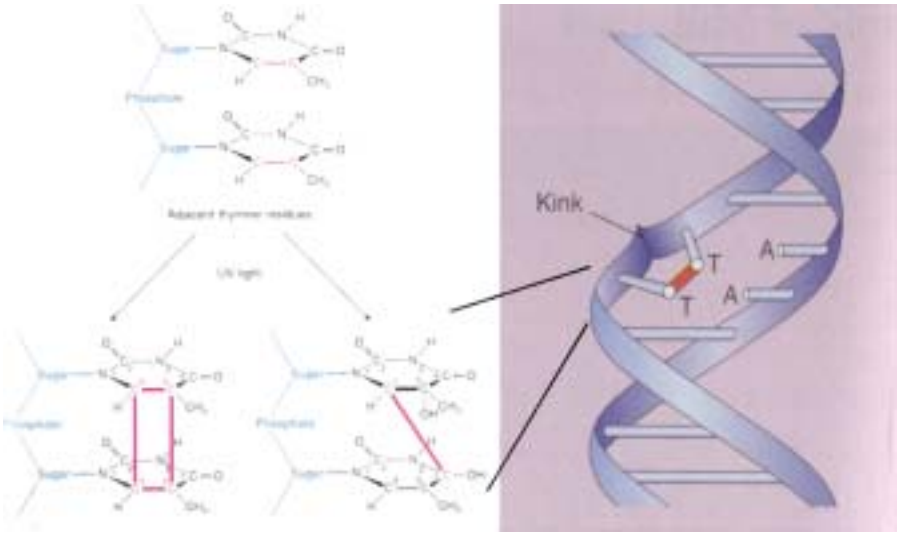


Figure 2-4. Formation of Thymine Dimers (Raven and Johnson, 1996; Mathews and Van Holde, 1996)

When this damaged DNA replicates, nucleotides do not complementary base pair with the thymine dimers and this terminates replication. Organisms may also replace thymine dimers with faulty base pairs, which causes mutations, leads to faulty protein synthesis, and may result in death.

The effect of thymine dimer formation may be reversed to some extent by exposure to visible light in a process called photoreactivation. Visible light can activate the enzyme DNA photolyase that breaks the bond joining the thymine bases. DNA can also be repaired by excision, where DNA polymerase and DNA ligase cut out damaged DNA and replace it with a stretch of error-free DNA (Mathews and Van Holde, 1996).

When DNA damage is too extensive for photoreactivation and excision mechanisms, the cell coordinates the expression of a large number of unlinked genes, which enhance capacity for DNA repair and inhibit cell division. This orchestrated activation of diverse

metabolic functions to repair damaged DNA damage has been called the SOS response (Mathews and Van Holde, 1996). The manifestation of the SOS response eventually leads to DNA repair and returns the cell to its normal growth cycle.

Extreme UV-resistance of some bacteria is a result of efficient DNA repair machinery along with powerful scavenging activity of cells toward various reactive oxygen species generated by UV irradiation (reactive oxygen species are discussed in the next section). To ensure UV-A radiation overpowers pathogenic cellular defense mechanisms, a sunlight intensity of 500 W/m^2 should be applied for 3 to 5 hours to induce lethal effects (SODIS News No. 1, 1998). UV-A also creates highly reactive oxygen species as a secondary disinfection product in a process called photo-oxidative disinfection.

2.4 Photo-Oxidative Disinfection

UV-induced reactive oxygen species can be lethal if they are present in numbers higher than the organism is capable of attenuating. Natural dissolved organic matter can absorb ultraviolet radiation to induce photochemical reactions (Miller, 1998). The energy transfer of a high-energy photon to absorbing molecule produces highly reactive species such as superoxides (O_2^-), hydrogen peroxides (H_2O_2), and hydroxyl radicals (OH·) (Stumm and Morgan, 1995; Miller 1998). These highly reactive species in turn oxidize microbial cellular components such as nucleic acids, enzymes, and membrane lipids, which kill the microorganisms (McGuigan *et al.*, 1999; Reed 1996; Reed 1997).

In their defense, microorganisms have evolved powerful scavenging activity toward various reactive oxygen species. (Yun *et al.,* 2000; Fridovich, 1988; Halliwell, and Gutteridge, 1999). A common defense against superoxide is carried out by a group of enzymes called superoxide dismutase. Superoxide dismutase catalyzes the following reaction, which decreases the lifetime of superoxide by a factor of 10^9 (Fridovich, 1998):

$$O_2^- + O_2^- + 2H^+ \rightarrow H_2O_2 + O_2$$

Microbes cope with hydrogen peroxides using two groups of enzymes called catalases and peroxidases. Catalases eliminate hydrogen peroxide by:

$$2H_2O_2 \rightarrow O_2 + 2H_2O$$

while peroxidases uses the reducing power of *NADH*:

$$H_2O_2 + 2NADH \rightarrow 2NAD^+ + 2H_2O$$

In addition to superoxide dismutases, catalases, and peroxidase, there is an additional orchestrated defense observed in *E. coli* involving the SoxRS and OxyR regulons. When activated, these regulons express several genes to provide additional defense (Fridovich, 1998).

Superoxide and hydrogen peroxide are not themselves dramatically devastating, but they can produce hydroxyl radicals, which form a juggernaut of oxidative power, in two ways:

$$1.\ H_2O_2 + e^- + H^+ \rightarrow H_2O + OH\cdot$$

$$2a.\ M^{3+} + O_2^- \rightarrow M^{2+} + O_2$$

$$2b.\ M^{2+} + H_2O_2 \rightarrow OH^- + M^{3+} + OH\cdot$$

where M is a metal

After the hydroxyl radical if formed, it reacts extremely fast with almost every type of molecule found in living cells causing tremendous damage.

For photo-oxidative disinfection to occur, sufficient levels of oxygen need to be initially present. This was demonstrated by Reed in 1997 by comparing aerobic and anaerobic inactivation rates *E. coli* and *Ent. faecalis* using solar disinfection.

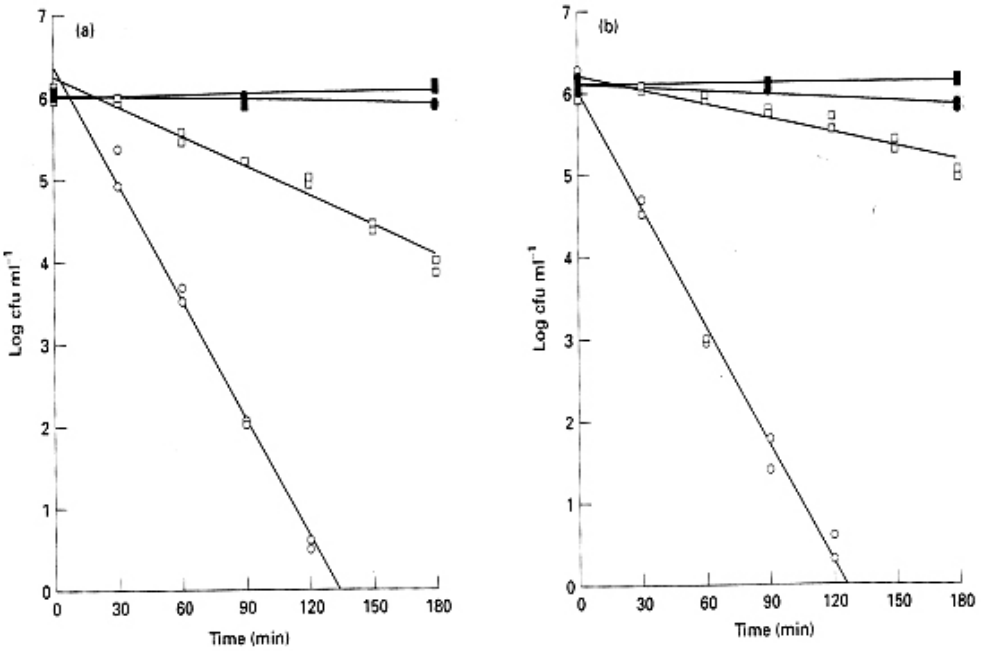


Fig. 1 Inactivation of exponential phase (a) *Escherichia coli* and (b) *Enterococcus faecalis*, either in full sunlight under aerobic (○) or anaerobic (□) conditions, or in darkness under aerobic (●) or anaerobic (■) conditions

Figure 2-5. Aerobic vs. Anaerobic Microbial Inactivation (Reed, 1997).

The aerobic rates of disinfection (circles) are much faster than the anaerobic rates (squares), indicating that the presence of oxygen is essential for the rapid solar destruction of *E. coli* and *Ent. faecalis.*

Reed's experiments demonstrated the importance of oxygen to SODIS. This desired aeration can be achieved on a practical level by vigorously shaking the SODIS containers before sunlight exposure. This is especially important for stagnant water sources where the levels of dissolved oxygen are questionable (EAWAG/SANDEC, Technical Notes).

2.5 Thermal Inactivation

Thermal effects can act synergistically in the disinfection process if they can overcome microbial heat resistance. As temperatures rise past the maximum growth value, it becomes difficult for proteins to form their proper structures and it causes already formed proteins to unfold. Denatured proteins do not function properly and may eventually kill the organism (Brock, 2000).

Microorganisms have special chaperone proteins that are especially suited for elevated temperatures due to better hydrogen bonding, superior hydrophobic packing, and enhanced secondary structure. These heat shock proteins are present in low concentrations under normal conditions, but are expressed at high levels when exposed to a sudden increase in temperature. These proteins help keep other proteins functional and can cause heat resistance (Brock, 2000). The efficacy of these heat-shock proteins determines how much temperature an organism can withstand before heat inactivation.

It has been observed that water temperatures between 20 and 40 ° C do not affect the inactivation of *E.coli* by sunlight (Wegelin *et al.*, 1994). However, synergistic effects are observed at a water temperature of 45 ° C (McGuigan *et al.*, 1998). Compared to lower

water temperatures, only one-third of the UV-A fluence was required to inactivate E. coli at synergistic threshold of 50 ° C (Wegelin *et al*., 1994). SODIS technical notes show the synergistic relationship between UV-A and thermal disinfection depicted in Figure 2-7.

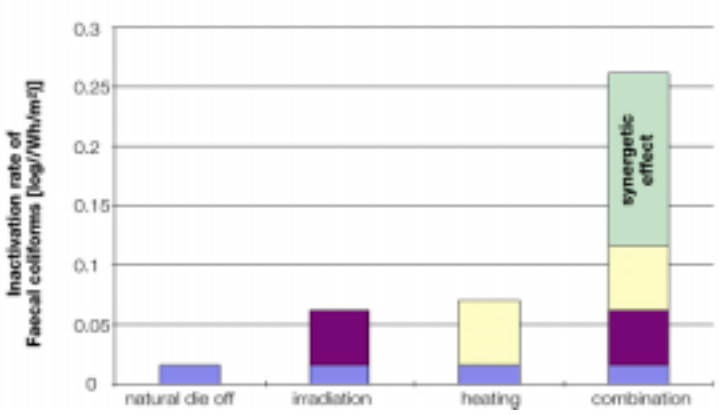


Figure 2-6. Synergistic effects of UV and Temperature (EAWAG/SANDEC, Technical Notes)

To increase thermal effects, bottles are painted black at the bottom. Black by definition is the absence of color and therefore it absorbs many wavelengths from the electromagnetic spectrum, which converts light energy into heat. The half-blackened SODIS bottles increase the temperature by approximately 5 ° C. Additionally, placing the bottles on dark surfaces will also help heat the water and produce thermal effects (EAWAG/SANDEC, 1998).

The combined effects of sunlight-induced DNA alteration, photo-oxidative destruction, and thermal inactivation are responsible for the inactivation of microorganisms, which is well documented.

2.6 Inactivation of Indicator Organisms and Pathogens

SODIS efficacy is usually established through the inactivation of indicator organisms, but effects on actual pathogens have also been investigated. A brief overview of indicator organisms will be given, as they are the most commonly used gauges of SODIS success. This will be followed by a tabulation of microorganisms that are inactivated by SODIS and a table of the heat sensitivities of some pathogens will also be provided, as thermal effects are an important aspect of the SODIS process.

2.6.1 Indicator Organisms

A person discharges billions of organisms per day and most of the pathogenic fraction of these organisms is difficult to isolate and identify. Consequently, the presence of easily identifiable organisms is used to suggest the existence of pathogenic ones. The characteristics of an ideal indicator organism are shown in Table 2-1.

Table 2-1. Criteria for an Ideal Indicator Organism (Maier *et al.*, 2000)

Used for all types of water
Present whenever enteric pathogens are present
Should have a reasonably longer survival rate than pathogens
Should not grow in water
Testing method should be easy to perform
Density should allude to extent of fecal pollution
Should be a member of the microflora of warm-blooded animals

Unfortunately, no single group of organism meets all of the above criteria. Consequently, multiple indicator organism groups are often used. The two most common ones are total and fecal coliform.

2.6.1.1 Total Coliform

Coliform bacteria include the genera *Escherichia, Enterobactor,* and *Klebsiella* and are characteristically facultatively anaerobic, gram-negative, non-spore-forming, rod-shaped bacteria that can ferment lactose to produces gas (Maier et al., 2000). Traditionally, coliform quantity has served as the standard to gauge water quality with respect to pathogens.

Experience has shown that the absence of coliform bacteria in 100 ml of drinking water will prevent enteric diseases. Two realizations have been made to support this observation. First, relatively few individuals excrete pathogens while the entire population contributes coliform to the waste stream. Therefore, the number of coliform should far exceed the number of pathogens as shown for infectious viruses by Table 2-2.

Table 2-2.Virus-Coliform Ratios for Sewage and Polluted Surface Waters (Masters, 1997)

	Virus	Coliform	Virus/Coliform Ratio
Sewage	500/100 ml	$46*10^6$/100 ml	1:92,000
Polluted Surface Water	1/500 ml	$5*10^4$/100 ml	1:50,000

Second, the survival rate of pathogens outside of the host is much lower than the survival rate of coliform bacteria. The combination of these two factors statistically suggests that it is extremely unlikely to have water containing pathogens without numerous coliform. However, coliform bacteria have characteristics that make them less than an ideal indicator organism: regrowth in tropical waters, suppression of numbers by background

bacterial growth, some eukaryotic organisms like *Giardia* can survive considerably longer outside their host, and not all coliform are of fecal origin.

2.6.1.2 Fecal Coliform and E. coli

To help eliminate possible false positives, coliform of only fecal origin can be used. These organisms consist of the *Escherichi* and *Klebsiella* genera. These coliforms can ferment lactose to produce both acid and gas at 44.5 ° C within 24 hours (Maier *et al.*, 2000). It has been suggested that *E. coli* be used as an indicator organism as it can readily be distinguished from other members of the coliform group. However, *E. coli* cannot be differentiated between human and animal origin. Despite these limitations, fecal coliform bacteria have proven invaluable in assessing drinking water quality as shown by Table 2-3:

Table 2-3. Indicator Organisms Used in Establishing Performance Criteria for Various Water Use (Metcalf and Eddy, 1991)

Water Use	Indicator Organisms
Drinking Water	Total coliform
Freshwater Recreation	Fecal coliform, *E. coli, Enterococci*
Saltwater Recreation	Fecal coliform, total coliform, *Enterococci*
Shellfish Growing Areas	Total coliform, fecal coliform
Agricultural irrigation	Total coliform (for reclaimed water)
Wastewater effluent disinfection	Total coliform, fecal coliform

In 1984, Acra demonstrated that *E. coli* serves as good indicator organism for SODIS as it is more resistant to the lethal effects of sunlight than other bacteria. Coliform bacteria have become the general standard in assessing microbial water quality but many other organisms have been put to the SODIS test.

2.6.2 Inactivation of Specific Microorganisms and Heat Sensitivity

Table 2-4 is a list of microorganisms that have been inactivated by the SODIS process. It is not comprehensive and the references for coliform bacteria are far more extensive. However, it demonstrates that many different microorganisms are sensitive to the SODIS method.

Table 2-4. SODIS Inactivation of Microorganisms

Microorganism	Reference:
E. coli	Wegelin *et al.*, 1994
Fecal Coliform	Sommer, 1997
Vibrio Cholera	Sommer, 1997
Vibrio Cholera	*New Scientist Magazine*, 2000
P. aerugenosa	Acra *et al.*, 1984
S. flexneri	Acra *et al.*, 1984
S. typhi	Acra *et al.*, 1984
S. enteritidis	Acra *et al.*, 1984
S. paratyphi	Acra *et al.*, 1984
Aspergillus niger	Acra *et al.*, 1984
Aspergillus flavus	Acra *et al.*, 1984
Candida	Acra *et al.*, 1984
Str. Faecalis	Wegelin *et al.*, 1994
Penicillium	Acra *et al.*, 1984
Polio Virus	Cubbage *et al.*,1979
Bacteriophage MS2	Kapuscinski and Mitchell, 1982
Enterocci	Wegelin *et al.*, 1994
Bacteriophage f2	Wegelin *et al.*, 1994
Encephalomyocarditis virus	Wegelin *et al.*, 1994
Rotavirus	Wegelin *et al.*, 1994
Cryptosporidium*	Bukhari *et al.*, 1999; Clancy *et al.*, 1998
Cryptosporidium	*New Scientist Magazine*, 2000
Giardia Muris*	Craik *et al.*, 2000

*Found under a UV lamp measured in the UV-C range. Although UV-C is not found in sunlight, it suggests these organisms would be sensitive to the UV-A portion of sunlight.

While this list does not address all of the important pathogens, there is active research to investigate important pathogens such as *Giardia* (SODIS Conference Synthesis, 1999). Some additional insight to other microorganisms could be gained by examining their thermal sensitivities, as thermal inactivation of microorganisms is a very important process in SODIS. Table 2-5 shows the heat sensitivities of several infectious organisms.

Table 2-5. Thermal Destruction of Microorganisms (Feachem *et al*., 1983)

Time and Temperature for 100% destruction			
Microorganism	**1 min**	**6 min**	**60 min**
Enteroviruses			62 °C
Rotaviruses	63 °C for 30 min		
Salmonellae		62 °C	58 °C
Shigella		61 °C	54 °C
Vibrio Cholera			45 °C
Entamoeba Histolytica cysts	57 °C	54 °C	50 °C
Giardia Cysts	57 °C	54 °C	50 °C
Hookworm eggs and larvae		62 °C	51 °C
Ascaris eggs	68 °C	62 °C	57 °C
Schistosomas eggs	60 °C	55 °C	50 °C
Taenia eggs	65 °C	57 °C	51 °C

The inactivation of microorganisms by the SODIS process is fairly well established. However, there has been some concern of secondary UV effects enhancing bacterial growth and the possible regrowth of enteric pathogens. These issues will now be examined.

2.7 UV-Enhanced Bacterial Growth and Bacterial Regrowth

Studies have shown that exposures of UV radiation can actually increase indigenous concentrations of bacteria (Moran and Zepp, 1997; Bertilsson *et al.*, 1999; Lindell *et al.*, 1995). Solar UV radiation may alter the chemistry of dissolved humic substances in water to produce lower molecular weight organic compounds, which serve as substrate for microorganisms (Mopper and Stahovec, 1986; Kieber *et al.*, 1989). Additionally, photochemical reactions can generate free ammonium in humic and natural waters (Bushaw *et al.*, 1996; Gao and Zepp, 1998). These effects of liberated food and nutrients can enhance bacterial growth. Furthermore, studies have shown that *E. coli* can regrow after UV-C inactivation (Mechsner and Fleischmann, 1990; Mechsner *et al.*, 1991; Mechsner and Fleischmann, 1992). These various factors suggest that it may be possible for pathogens to be present after short-term storage if given enough time to regenerate.

Wegelin *et al.* (1994) examined various aspects of microbial regrowth to show that sunlight and UV-C do not fully kill bacteria mixtures beyond regrowth, and *E. coli* could regenerate from UV-C radiation. However, there was no revival observed for *E. coli* inactivated by the SODIS process (Figure 2-7).

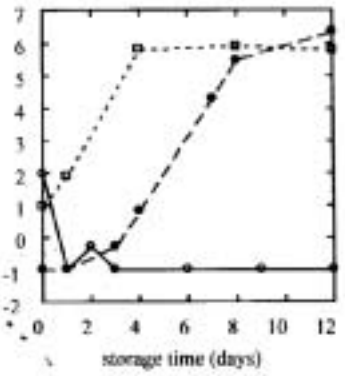


Fig. 15 Regrowth of *E. coli* and *bacterial mixtures* during increasing storage time of the irradiated suspensions. Temperature always at 20 °C. (●) *E. coli* irradiated using the undoped lamp and the 320 nm cut-off filter (fluence: 2240 kJ/m²); (○) *E. coli* irradiated with sunlight (fluence: 1070 kJ/m²); (□) bacterial mixtures irradiated with sunlight (fluence: 1470 kJ/m²). For $N < 0.5$, log N was set at −1.

Figure 2-7. Bacterial Regrowth (Wegelin *et al.*, 1994)

Wegelin *et al.* state that the difference in *E. coli* regrowth can be attributed to the relatively longer exposure time required to inactivate the cells with solar radiation when compared to the UV-C fluence. For the study conducted by Wegelin *et al.* (1994), the regrowth of natural bacteria from sunlight was attributed to the resistant saprophytic bacteria and their spores.

An interesting question for further research is, in general, why can indigenous microbial populations regenerate from the SODIS process while enteric pathogens are permanently inactivated? One can speculate that the indigenous aquatic microorganisms have much more developed DNA repair and reactive oxygen species defense mechanisms (as previously described). Evolution in an environment that has frequent exposure to UV and reactive oxygen species would cause the microorganisms that are most resistant to these

adverse effects to be most successful. This would cause microbial populations indigenous to aquatic systems to have greater UV and reactive oxygen species resistance. However, enteric pathogens have evolved in the dark anaerobic human gut and, consequently, there would be no selective pressure to produce such developed repair mechanisms against UV and reactive oxygen species. Consequently, when enteric pathogens are exposed to the SODIS process, they are inactivated while the indigenous populations can revive. Despite any bacterial revival, the aim of SODIS is to produce a pathogen-free source of water and not a sterile solution, which the study conducted by Wegelin *et al.* (1994) demonstrated.

The science behind SODIS has been discussed. However, SODIS efficacy is highly dependent on site-specific conditions. These conditions along with some practical aspects must be considered before applying SODIS.

3 Important SODIS Variables

SODIS operates on the principle that sunlight-induced DNA alteration, photo-oxidative destruction, and thermal effects will inactivate microorganisms. For these parameters to be effective, the environment must be sunny and hot enough, the water must be clear enough to allow the light to penetrate, and the type of bottle being used must not substantially hinder these processes. In addition, for this technology to become a reality, people must be able to afford it, and they must believe in it, or it would never be applied. Haiti's climate as it relates to SODIS will be discussed, including an approach to simulate sunshine intensities. This will be followed by a discussion of the social acceptance observed in different parts of the world along with economic considerations.

3.1 Haitian Climate

Assuming there is adequate oxygen to mix into the water, the two most influential variables affecting SODIS efficacy are sunshine and temperature. These two parameters are a function of seasonal and geographical climate variation. To assess these factors, Haiti is discretized into seven sections that correspond to the degree latitude and longitude data obtained from NASA Langley Atmospheric Sciences Data Center (Figure 3-1).

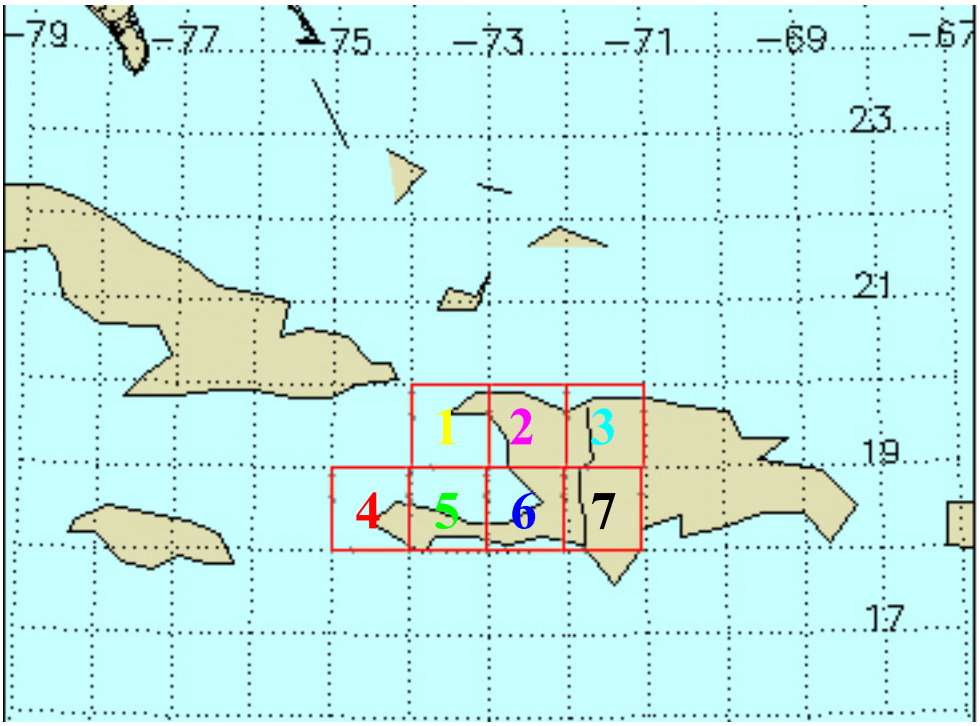


Figure 3-1. Discretization of Haiti (NASA Langley Research Center Atmospheric Sciences Data Center, 2001)

Based on this discretization, seasonal Haitian sunshine and temperature will be examined followed by influences of topography.

3.1.1 Haitian Sunshine

The sun is a giant fusion reactor that destroys matter to yield energy in the form of electromagnetic radiation. The earth is partially shielded from solar radiation by absorption, scattering, and reflection in the stratosphere and troposphere (Brooks and Miller, 1963; McVeigh, 1977; Sabins, 1978; Michaels, 1979; WHO, 1979).

Stratospheric ozone strongly absorbs shorter wavelength radiation while its affinity decreases rapidly with higher wavelengths. This high-energy absorption blocks the earth

from UV-C and only allows a fraction of UV-B and UV-A to reach ground level (Acra, 1990). Solar attenuation in the troposphere is primarily caused by clouds, dust, smoke, haze, smog, and various gases. Tropospheric scattering highly depends on particle size and produces both selective and nonselective scattering. Selective scattering is caused by smoke, fumes, haze, and gas molecules that are smaller than or equal to the incident radiation wavelength. This type of scattering affects shorter wavelengths and is more severe for polluted atmospheres. Nonselective scattering is caused by dust, fog, and cloud particles with sizes more than 10 times the wavelength of the incident radiation. In addition, thin clouds may reflect less than 20% of the incident solar radiation, while thick clouds may reflect over 80% of all radiation (Acra, 1990).

Atmospheric attenuation causes the amount of solar radiation that reaches the earth's surface to be highly dependent on the path length through the atmosphere. This path length is a function of the earth's tilt, rotation, and slightly elliptical orbit. As the earth rotates around the sun, its axis is tilted constantly at 23.47°. During summer, the hemisphere tilts towards the sun, which causes the radiation to be more perpendicular and of greater duration. In winter, the hemisphere tilts away from the sun creating a longer atmospheric path and shorter days. A gradual transition occurs between these two extremes, giving seasonal changes. NASA Langley Atmospheric Sciences Data Center provides visualization for Haiti of a 10-year average monthly value of total daily radiation (Figure 3-2).

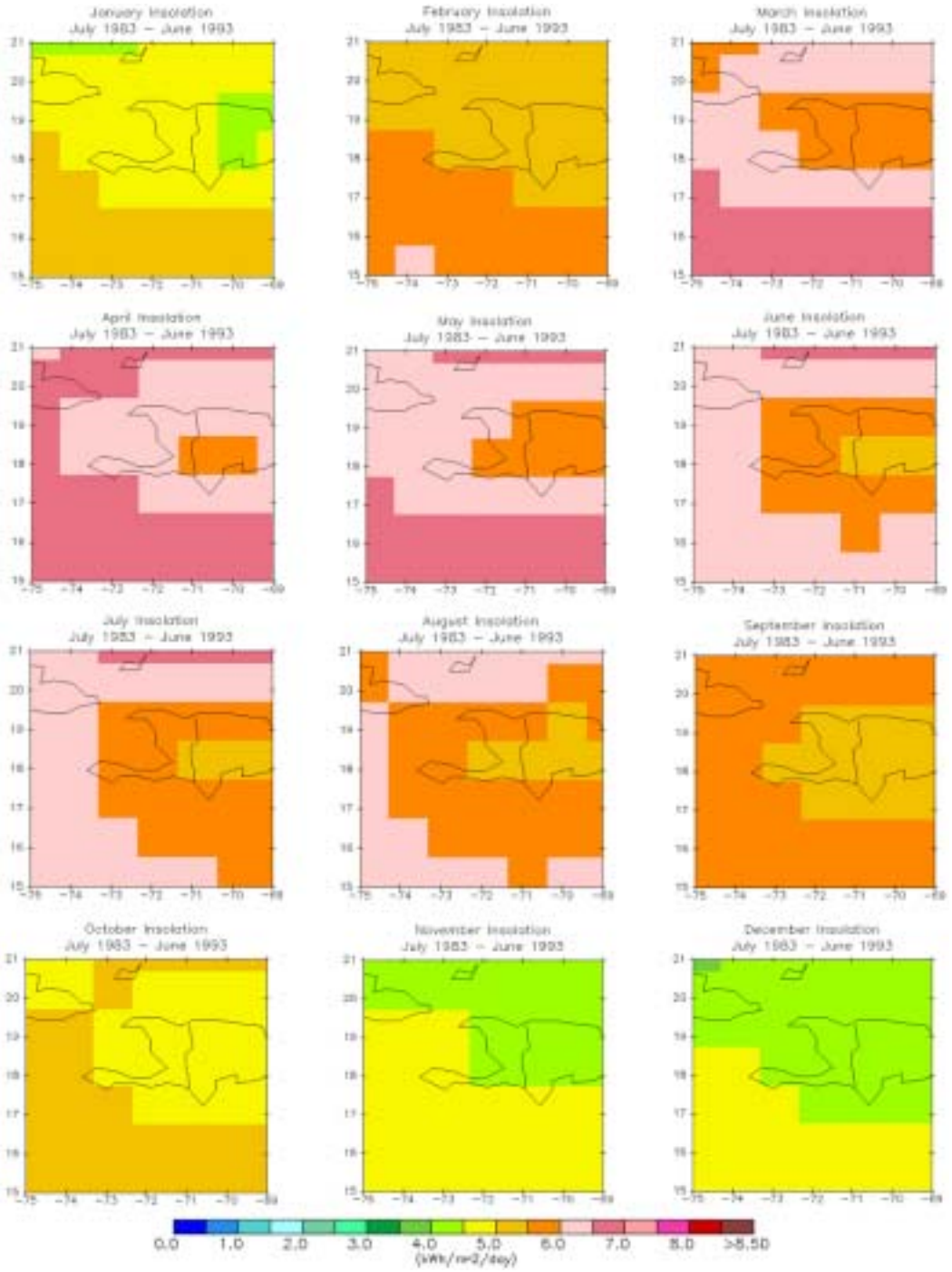


Figure 3-2. Average Monthly Value of Total Daily Radiation (NASA Langley Research Center Atmospheric Sciences Data Center, 2001)

The monthly amount of total surface radiation provides important information for assessing SODIS. However, recommendations for SODIS are based on a threshold of

sunlight intensities rather than the total amount of energy received. Fortunately, these two entities are intimately related and can be sufficiently described by mathematical models.

3.1.2 Mathematical Development of Sunshine Simulation

SODIS efficacy depends on an adequate duration of sunshine radiation. It has been deduced that an intensity of 500 W/m^2 should be available for 3 to 5 hours for effective disinfection (SODIS News No. 1, 1998). A value of at least 5 hours of sunshine above 500 W/m^2 will be used as a conservative threshold. Many areas of the world in need of SODIS are developing countries, and consequently, do not have meteorological data on sunshine intensity profiles. However, NASA Langley Atmospheric Sciences Data Center provides web accessible data on the 10-year average, minimum, and maximum amount of total energy received for a representative day of each month. This data has a spatial resolution of one-degree latitude and longitude for the entire world. Quantitative knowledge of the total amount of daily energy received, allows for the simulation of daily sunshine intensity profile. This information can then be used to calculate the average, minimum, and maximum intensity for the peak five hours of sunshine to get a first approximation of whether SODIS would be applicable for any given month. This technique will be applied to simulate Haitian sunshine but could be easily extended to simulate monthly sunshine values for anywhere in the world.

The general approach is to calculate the day length based on location and time of the year, which involves the earth's declination angle and sunrise angle. Next, the sun's hour angle relative to the location is obtained. This combined information is then used to determine what fraction of the total radiation is received at a given hour, ultimately

generating daily sunshine profile. The meanings and calculations for each necessary parameter will now be discussed.

The declination, ω_d, is the angular distance at solar noon between the sun and the equator, referenced as north positive. Declination changes with date and is independent of location. It has maximum absolute value of 23.45 degrees during the summer and winter solstice and 0 degrees on the equinoxes. It can be approximated for a specific Julian day from the equation given by Cooper (1969).

$$\omega_d = 23.45 \sin\left(\frac{360\left(284 + n_{Jday}\right)}{365}\right) \qquad (1.1)$$

where:
ω_d = *declination angle* [°]
n_{Jday} = *julian day* (*number of days after January* 1)

For practical purposes, Duffie and Beckman (1980) provide a table with declination angles that are representative of each month:

Table 3-1. Recommended average day for each month (Duffie and Beckman, 1980)

Month	Date	Julian Day	Declination, ω_d, [°]
January	17	17	-20.9
February	16	47	-13.0
March	16	75	-2.4
April	15	105	9.4
May	15	135	18.8
June	11	162	23.1
July	17	198	21.2
August	16	228	13.5
September	15	258	2.2
October	15	288	-9.6
November	14	318	-18.9
December	10	334	-23.0

*Values do not account for leap year; correct by adding 1 to months from March onward. Declination will also change slightly

The hour-angle, ω_t, is the angular displacement of the sun east or west of the local meridian due to rotation of the earth at 15° per hour. The hour-angle can be calculated from the following equation (Brock, 1980).

$$\omega_t = (t-12)15$$

$$\begin{aligned} &\textit{where}: \\ &\omega_t = \textit{hour-angle}\,[^\circ] \\ &t = \textit{time from midnight}\,[hr] \end{aligned} \tag{1.2}$$

The sunset or sunrise hour-angle, ω_s, is the hour-angle when the sun's center reaches the horizon and can be computed if the location's latitude, L, and current declination, ω_d, are known (Milankovitch, 1930).

$$\omega_s = \cos^{-1}\left(-\tan(L)\tan(\omega_d)\right)$$

$$\begin{aligned} &\textit{where}: \\ &\omega_s = \textit{sunrise or sunset angle}\,[^\circ] \\ &L = \textit{latitude}\,[^\circ] \end{aligned} \tag{1.3}$$

From the sunset angle, the day length, Dl, can be calculated:

$$Dl = 2\left(\frac{\omega_s}{15}\right)$$

$$\begin{aligned} &\textit{where}: \\ &Dl = \textit{day length}\,[hr] \end{aligned} \tag{1.4}$$

The total daily average solar radiation, I_{da}, can be obtained from NASA's website by degree latitude and longitude for everywhere on earth (NASA Langley Research Center Atmospheric Sciences Data Center, 2001). The hourly averages can be calculated by determining the ratio, r_t, of hourly amount radiation to the daily total (Duffie and Beckman, 1980):

$$r_t = \frac{\pi}{24}\left(a + b\cos\omega_t\right)\frac{\cos\omega_t - \cos\omega_s}{\sin\omega_s - (2\pi\omega_s/360)\cos\omega_s}$$

where:
r_t = *ratio of hourly to daily sunshine*
a = *coefficient*
b = *coefficient*

(1.5)

The coefficients *a* and *b* are:

$$a = .409 + .5016\sin(\omega_s - 60)$$
$$b = .6609 - .4767\sin(\omega_s - 60)$$

(1.6)

With this ratio known, the average hourly value can be calculated:

$$I_{ta} = r_t I_{da}$$

where:
I_{ta} = *average hourly radiation* $[W/m^2]$
I_{da} = *average daily radiation* $[Wh/m^2]$
r_t = *ratio of hourly to daily radiaiton*

(1.7)

This information was used to create a computer code, provided in the Appendix, to simulate diurnal sunshine profiles. The model is essentially a Fourier series that uses the amount of total sunshine and the day length to produce correct amplitude and wavelengths of the period function that simulates diurnal sunshine. The algorithm produces the following shape for 74 hours (Figure 3-3).

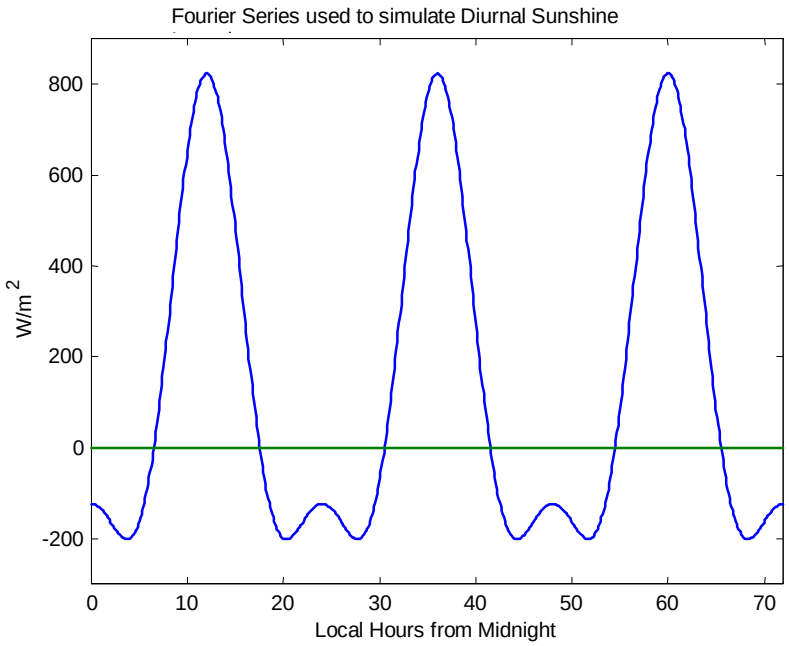


Figure 3-3. Fourier Series of Sunshine Intensity for 3 days Starting and Ending at Midnight

For the specific parameters used to generate this profile, the sun rises around 6 A.M. and sets around 6 P.M. The model assumes that solar noon is exactly at noon, the time at which the solar angle is 0 as calculated by equation 1.2. This can cause the model to be slightly out of phase with observed data. Solar time can differ from standard time for two reasons. First, there is a constant correction for the difference in longitude between the reference location and the meridian on which the local standard time is based. Second, there are perturbations in the earth's rate of rotation, which are taken into account by the equation of time. The overall adjustment from solar time to standard time is given by equation 1.8 (Duffie and Beckman, 1980).

$$solar\ time = standard\ time + 4(L_{st} - L_{loc}) + E$$

$$\begin{aligned} &where: \\ &solar\ time = time\,[minutes] \\ &standard\ time = time\,[minutes] \\ &L_{st} = standard\ local\ meridian\,[°] \\ &L_{loc} = local\ longitude\,[°] \\ &E = equation\ of\ time\,[minutes] \end{aligned} \tag{1.8}$$

Time adjustments can also be interpolated from Table 3-2.

Table 3-2. Adjustment for Daily Time (Wunderlich, 1972)

	Adjustment amount [minutes] for corresponding day of the month		
	1st	**11th**	**21st**
January	-3.58	-7.98	-11.38
February	-13.68	-14.35	-13.75
March	-12.38	-10.17	-7.32
April	-3.98	-1.11	+1.28
May	+2.95	+3.72	+3.57
June	+2.38	+0.60	-1.52
July	-3.62	-5.30	-6.23
August	-6.22	-5.01	-3.12
September	-0.03	+3.30	+6.85
October	+10.23	+13.17	+15.28
November	+16.33	+15.93	+14.12
December	+10.98	+6.78	+1.95

Adjusting for solar time is only important when trying to match observed data and not for simulating peak five-hour intensities. The aforementioned approach of using daily total energy to generate intensity profiles will now be used to validate the model and then simulate Haitian sunshine.

3.1.3 Simulation of Haitian Sunshine

The average, minimum, and maximum peak 5-hour sunlight intensities will be simulated throughout the year after the mathematical model has been verified. Model validation will be made by comparing simulated intensity values to both measured intensities and intensity values obtained from NASA Langley Atmospheric Sciences Data Center.

Sunlight intensity profiles were measured with a Kipp and Zonen Solrad kit (Section III, 4.1) from January 12th to January 21st 2001. Integration of an average intensity profile yields the average total amount of energy observed in Haiti, which was 5394 Wh/m^2. This value is then plugged into the model to simulate an intensity profile, and this simulated profile is then compared to the average measured intensity profile to validate the model (Figure 3-4).

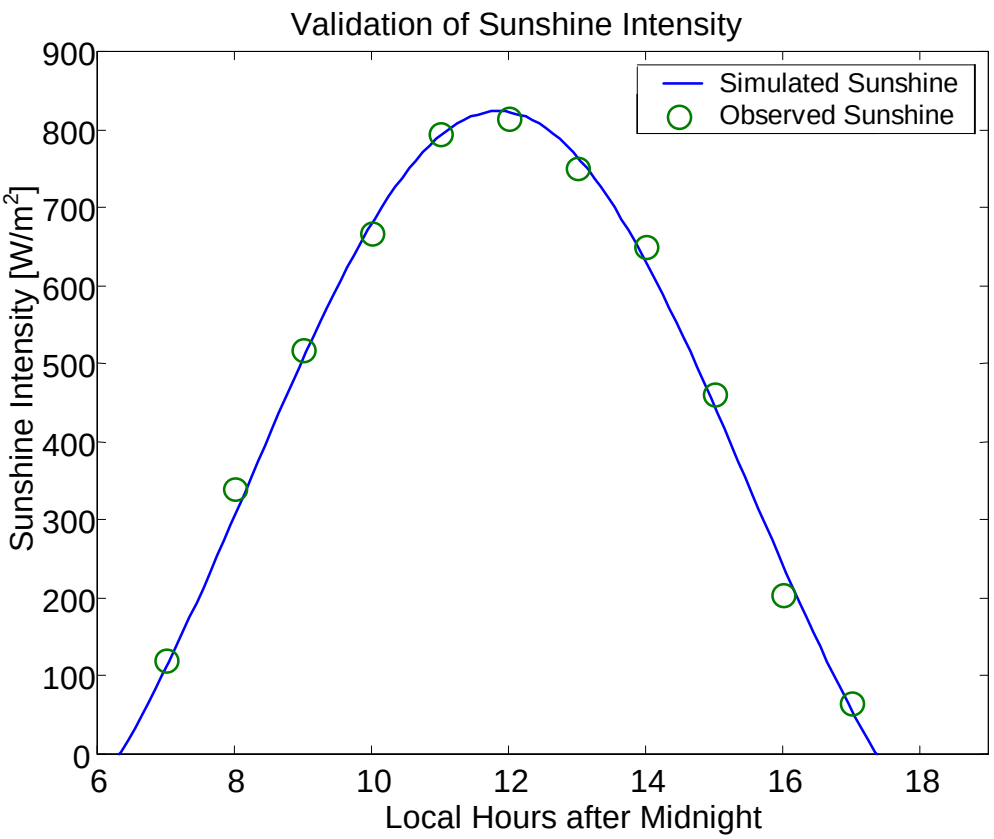


Figure 3-4. Model Validation of Simulated versus Observed Sunshine Intensity Profile

The model accuracy is demonstrated by its agreement within 99% of the measured values. A second validation is made using NASA Langley Atmospheric Sciences Data Center values for the average top three hours of sunshine intensity for each month of the year. Average monthly values of total energy are used to generate monthly intensity profiles as shown for Area 1 by Figure 3-5.

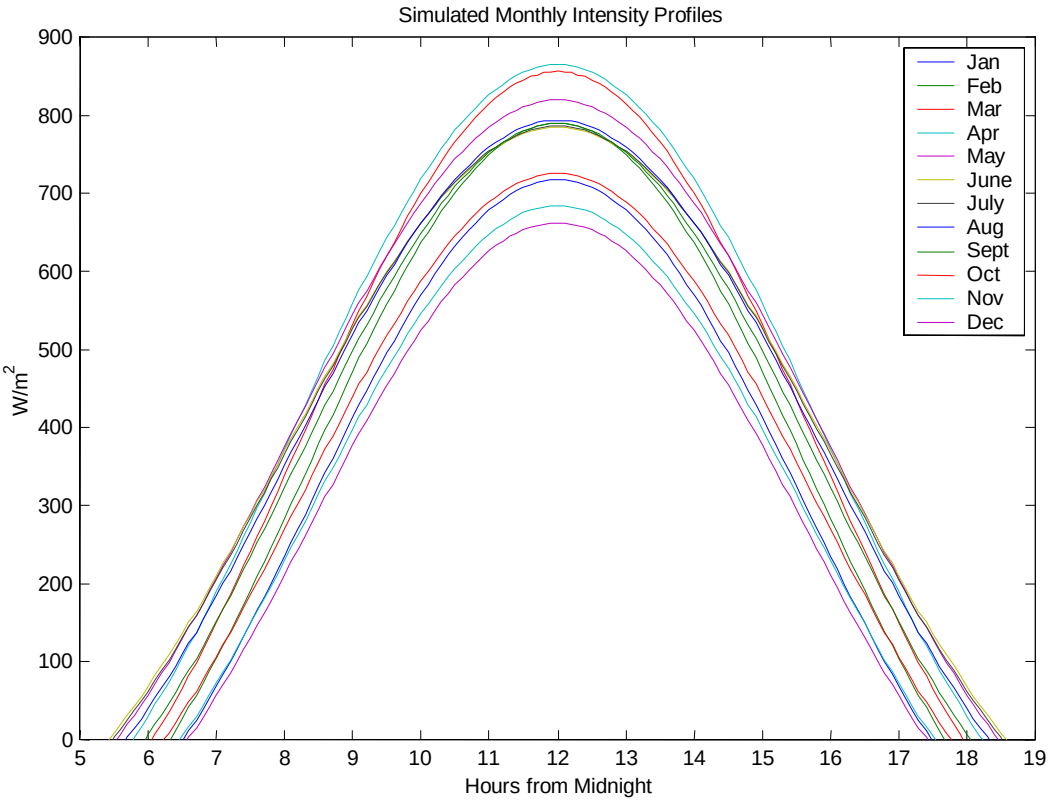


Figure 3-5. Simulated Intensity Profile for Each Month in Area 1 (NASA Langley Research Center Atmospheric Sciences Data Center, 2001)

From these monthly profiles, the peak three hours around noon are averaged for the first six areas used to discretize Haiti. These averaged values are then compared to the NASA data for each month of the year (Figure 3-6).

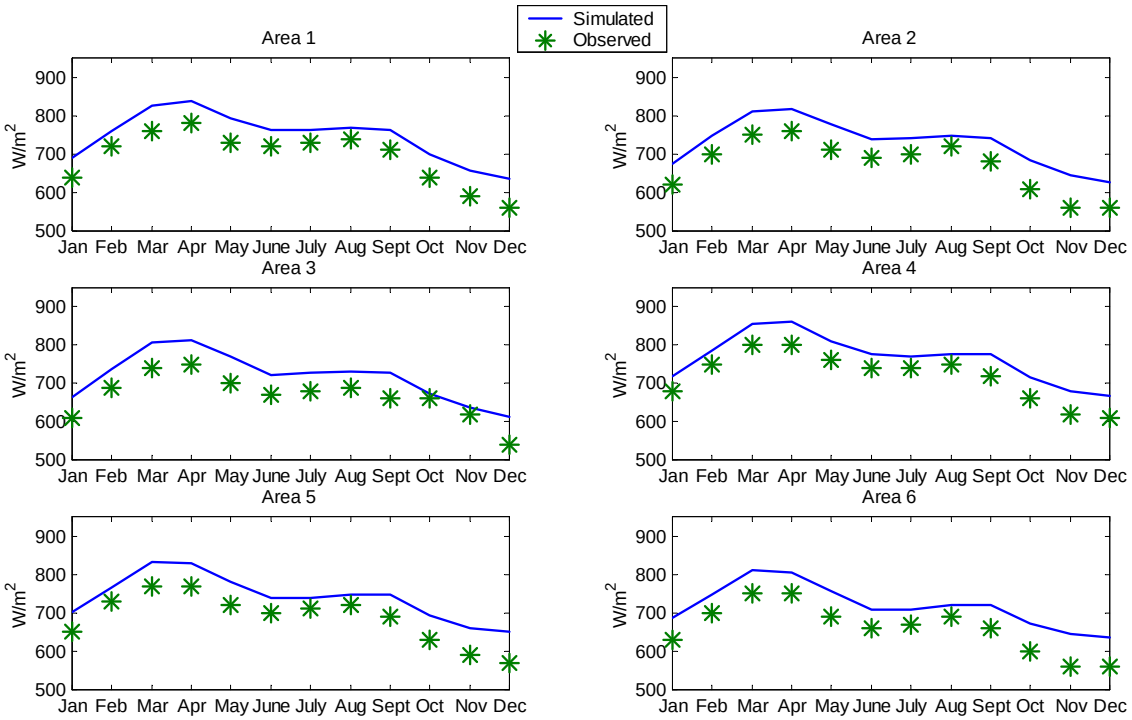


Figure 3-6. Comparison of Simulated to Observed Average Peak Three-Hour Average Intensities (NASA Langley Research Center Atmospheric Sciences Data Center, 2001)

Each area has an average correlation coefficient of .97 with a range of .98 to .95 between the predicted and the NASA data. The simulated versus the observed values for each area disagree by about 7.2% with a range of 6.2% to 8.1%. This span of error is well within the uncertainty on the NASA data of 14.2% (NASA Langley Research Center Atmospheric Sciences Data Center, 2001). Much of this difference can be attributed to the fact that the observed values are based on a 4-year intensity average, while the total energy used for the simulation is derived from a 10-year average.

With the model validated, the average peak five hours from the monthly intensity profiles are compared to the SODIS threshold of 500 W/m^2 (SODIS News No. 1, 1998). This

approach is applied to each of the seven areas used to discretize Haiti to assess potential SODIS application throughout the year (Figure 3-7).

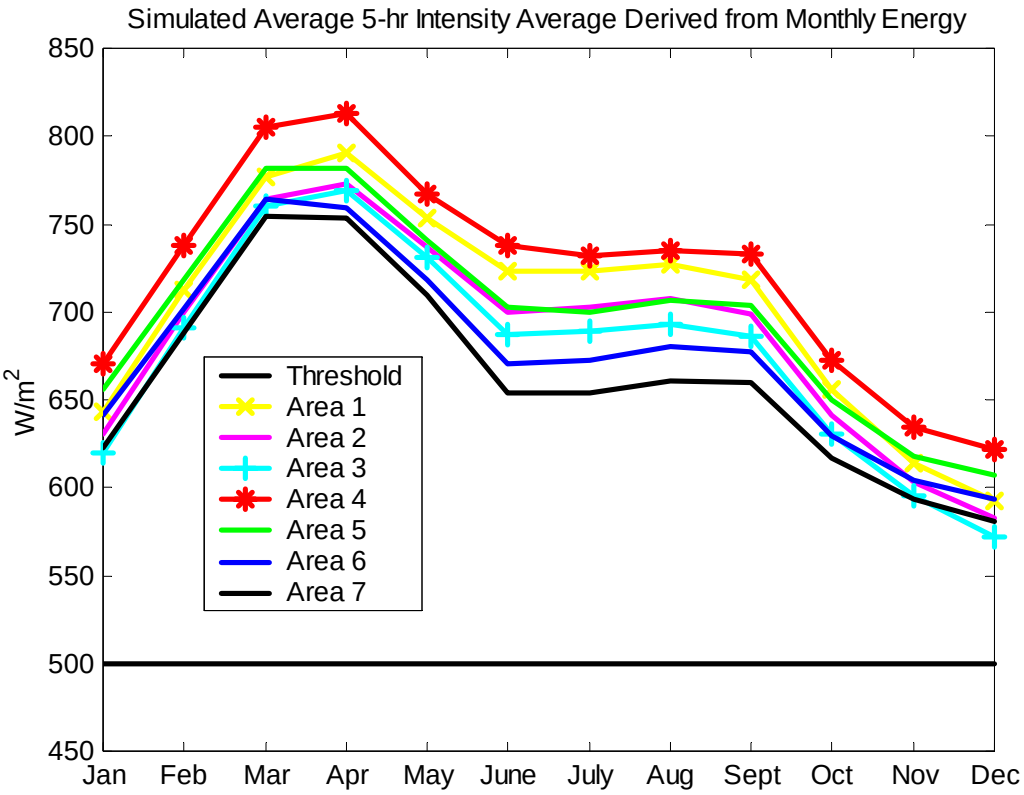


Figure 3-7. Yearly Five-Hour Average Intensity Profile of Haiti (NASA Langley Research Center Atmospheric Sciences Data Center, 2001)

These results show that Haitian sunshine is on average above the suggested disinfection threshold, which means that SODIS would be effective in Haiti for an average day throughout the year. However, Haitians still need to drink water during periods when there is not average sunshine. NASA Langley Research Center Atmospheric Sciences Data Center also provides data on the 10-year average monthly minimum and maximum total energy received. These values can be used to simulate minimum and maximum

5-hour intensity values using the previously described approach. Figure 3-8 shows the simulated results for the minimum expected 5-hr intensity profile.

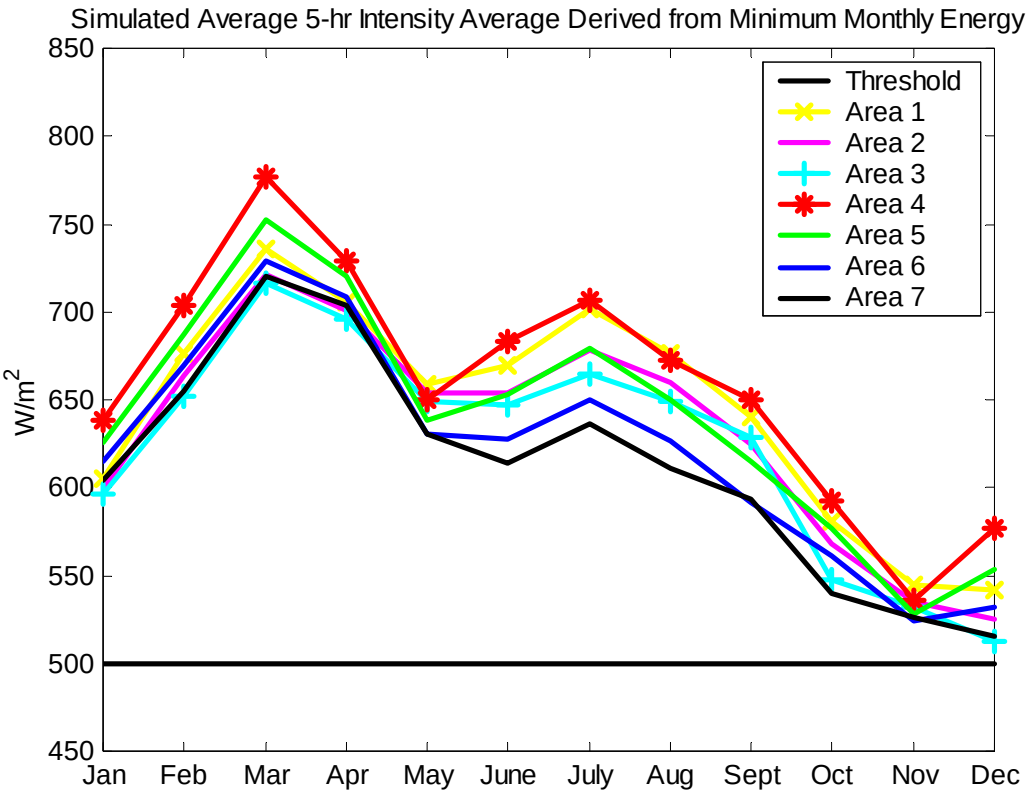


Figure 3-8. Yearly Five-Hour Minimum Intensity Profile of Haiti (NASA Langley Research Center Atmospheric Sciences Data Center, 2001)

Figure 3-8 shows that based on the 10-year average minimum values, SODIS should still be applicable. The large decrease in sunshine intensity during May coincides with Haiti's primary rainy season. This is reinforced by examining the yearly profile of daytime cloud cover for each area of Haiti (Figure 3-9).

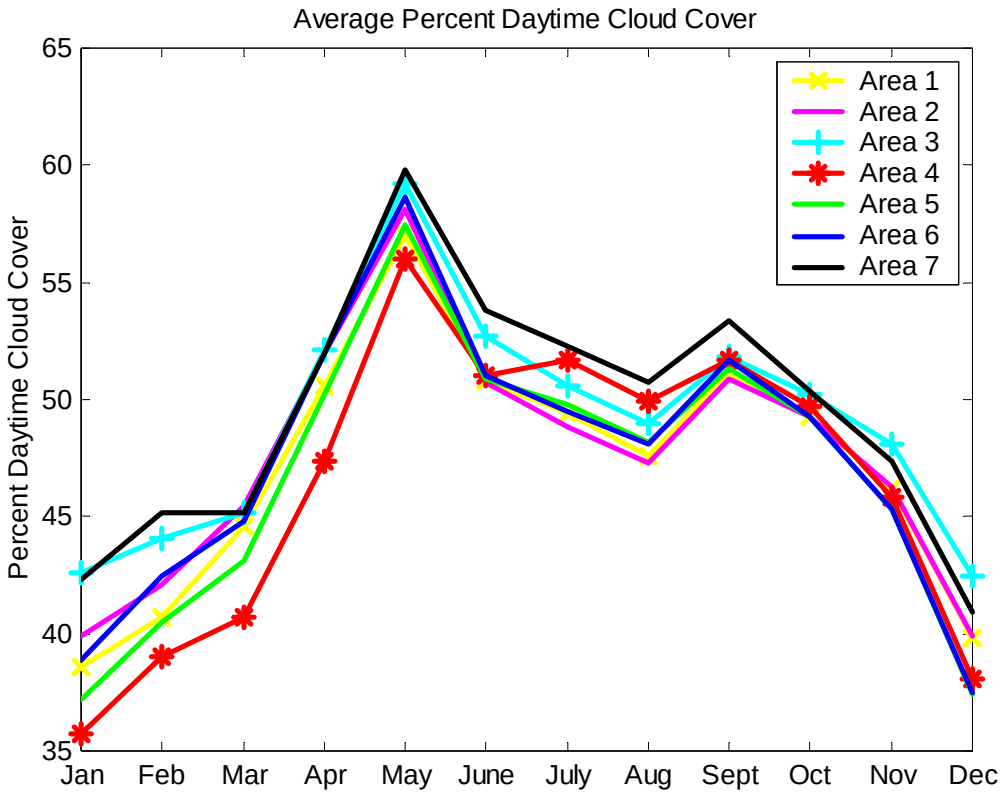


Figure 3-9. Average Percent Day Time Cloud Cover (NASA Langley Research Center Atmospheric Sciences Data Center, 2001)

As expected, there is an increase in percent cloudiness during May corresponding to Haiti's rainy season.

To establish expected upper bounds for the 5-hour intensity average for each month, the maximum total energies observed are used to generate intensity profiles as depicted by Figure 3-10.

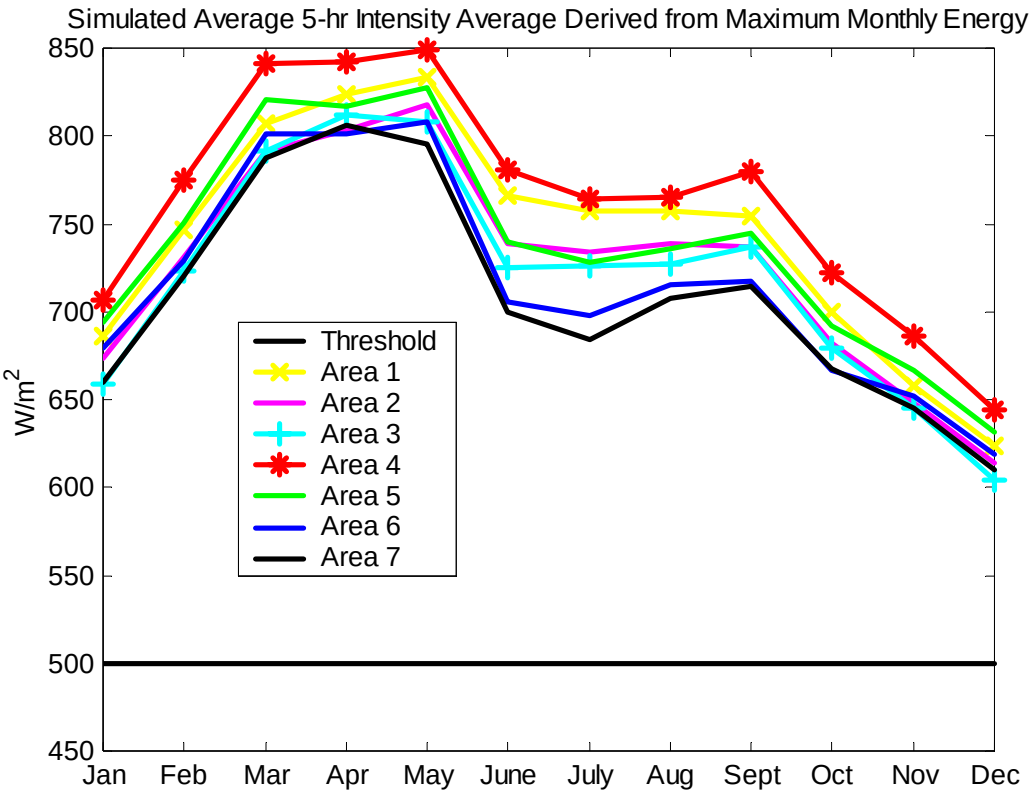


Figure 3-10. Yearly Five-Hour Maximum Intensity Profile of Haiti (NASA Langley Research Center Atmospheric Sciences Data Center, 2001)

These values are well above the SODIS threshold implying SODIS in Haiti should be extremely effective for sunny days.

A general sunshine intensity envelope for Haiti is obtained by examining the spatial averages across Haiti of the average, minimum, and maximum intensity values (Figure 3-11).

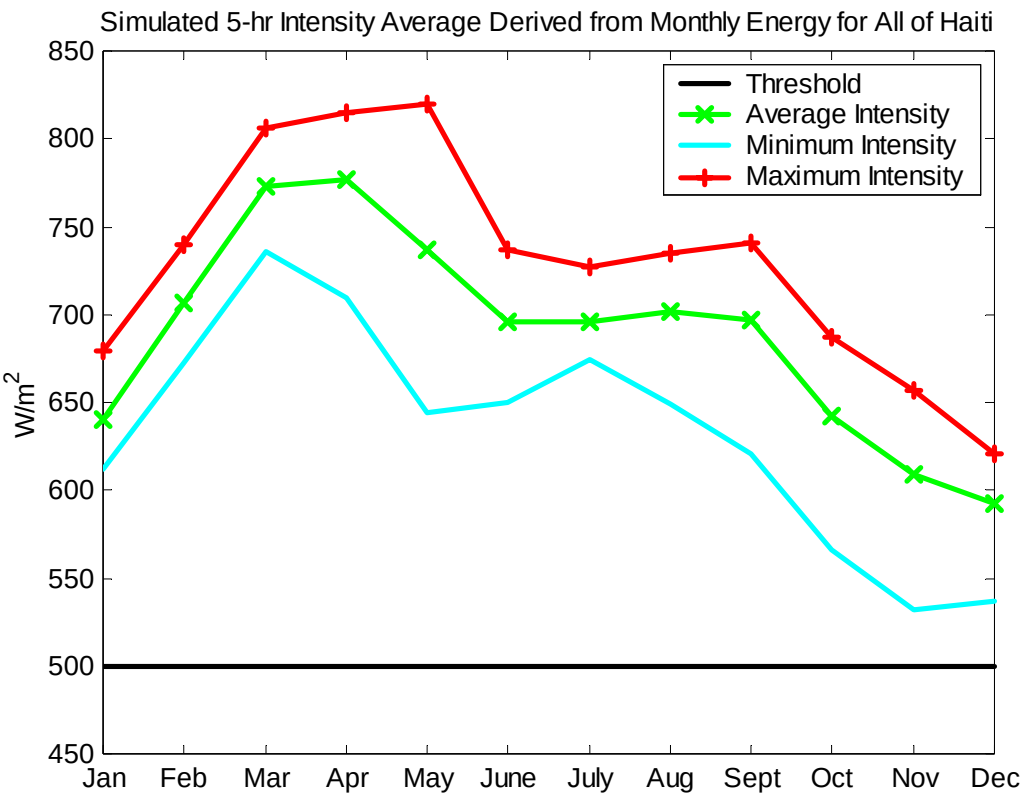


Figure 3-11. Yearly Five-Hour Average, Maximum, and Minimum Intensity Profile of Haiti (NASA Langley Research Center Atmospheric Sciences Data Center, 2001)

Figure 3-11 shows Haitian sunshine is on average above the recommend 5-hr average disinfection threshold and SODIS should be effective year-round in Haiti. However, it is important to note that these results are based on the discretization shown in Figure 3-1. The total energy values used to generate the intensity profiles are an average for each one of the grids and there could be substantial spatial variation within the spatial resolution of the model (which will be discussed further in section 3.1.5). This method of sunshine simulation is considered a good first approximation to assess the possible application of SODIS throughout the year in Haiti. The other important variable in the SODIS process that warrants investigation is temperature.

3.1.4 Haitian Temperature

To have synergistic sunlight and thermal effects in the SODIS process, water temperatures should reach at least 45 °C (McGuigan *et al*., 1998). Bottle temperature mainly depends on the amount of sunlight received and ambient temperature conditions. Section 3.1.3 shows that there is sufficient sunlight for the SODIS process, so ambient temperature conditions will be examined. Haiti has a warm tropical climate with average temperatures ranging from 24 °C in the winter to 28 °C in the summer. The average yearly temperature profile for the seven areas that compose Haiti is given by Figure 3-12.

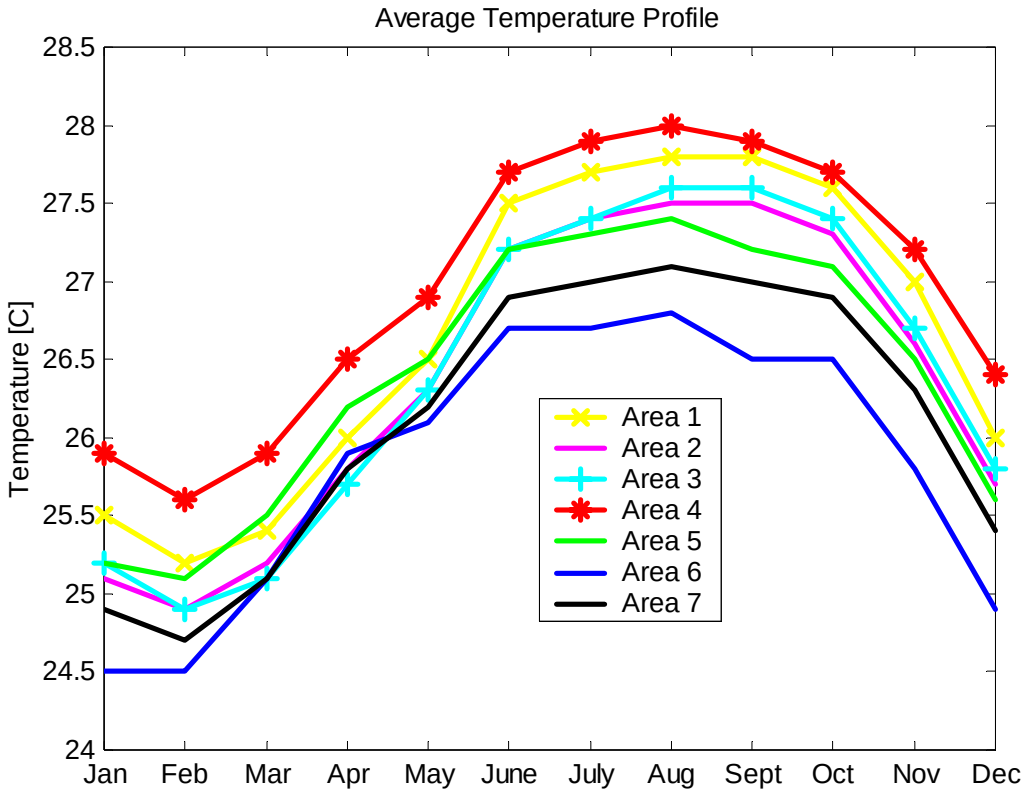


Figure 3-12. Average Temperature Profile (NASA Langley Atmospheric Sciences Data Center, 2001)

Figure 3-12 shows the temperature in Haiti is consistently warm throughout the year. In fact, the average annual temperature ranges are often below the daily temperature span. The breadths of the average daily temperature fluctuations for a given area are provided by Table 3-3.

Table 3-3. Average Monthly Temperature Range °C for Each Area (NASA Langley Atmospheric Sciences Data Center, 2001)

Area	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Average
1	2.65	2.72	2.87	2.76	2.40	2.29	2.21	2.13	2.00	2.17	2.24	2.42	2.41
2	3.36	3.44	3.64	3.54	3.10	3.01	2.89	2.77	2.56	2.74	2.83	3.05	3.08
3	2.57	2.65	2.78	2.68	2.33	2.21	2.12	2.04	1.95	2.12	2.21	2.36	2.34
4	2.75	2.84	3.02	2.88	2.50	2.42	2.39	2.27	2.09	2.21	2.33	2.52	2.52
5	4.76	4.88	5.18	5.07	4.43	4.36	4.30	4.07	3.64	3.79	3.96	4.30	4.40
6	6.76	6.91	7.35	7.25	6.35	6.29	6.21	5.86	5.18	5.37	5.60	6.08	6.27
7	4.62	4.75	5.03	4.94	4.30	4.19	4.11	3.90	3.53	3.71	3.87	4.19	4.26

The high amount of sunshine Haiti receives and Haiti's consistent warmth, suggests that bottle temperatures should usually reach above the synergistic threshold. However, topographical effects can have strong influences on both local sunshine and temperature.

3.1.5 Haitian Topography

The Native American Indian inhabitants called the island Ayti, meaning "Mountainous Land." Approximately 63% of all land in Haiti have slopes greater than 20% and only 29% have slopes of less than 10% (USAID, 1985). Haiti's heterogeneous terrains create highly variable microclimates with a large range of sunshine, temperature, and rainfall. Haiti's major regions consist of mountains, plateaus, and plains (Figure 3-13).

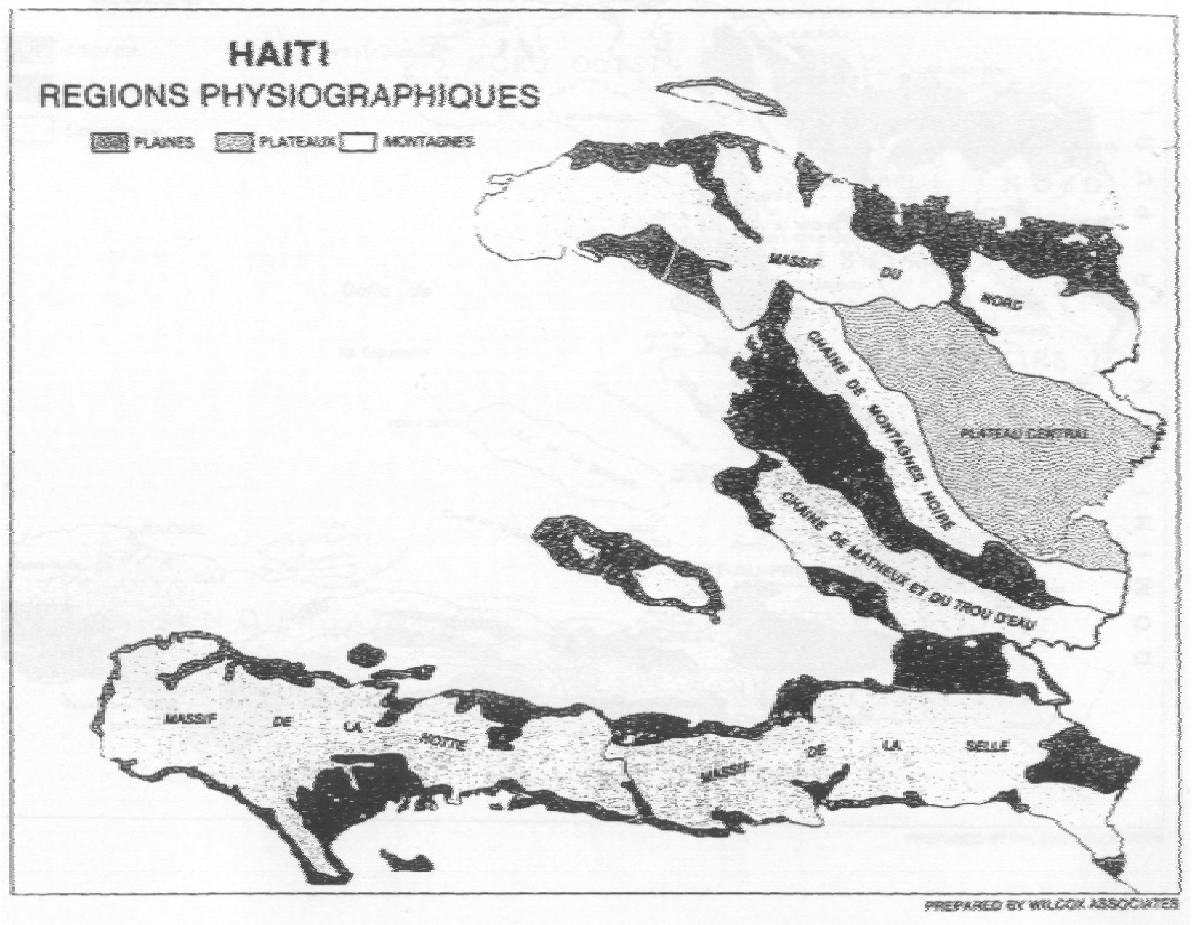


Figure 3-13. Physiographical regions of Haiti (USAID, 1985)

The Massif de la Hotte and the Massif de la Selle, are home to the country's highest peak of 2,684 meters above sea level and run west to east in southern Haiti. The Central Plateau contains smaller mountains extending northwest along the peninsula (USAID, 1985). A more general contour map of Haitian elevation is given by Figure 3-14.

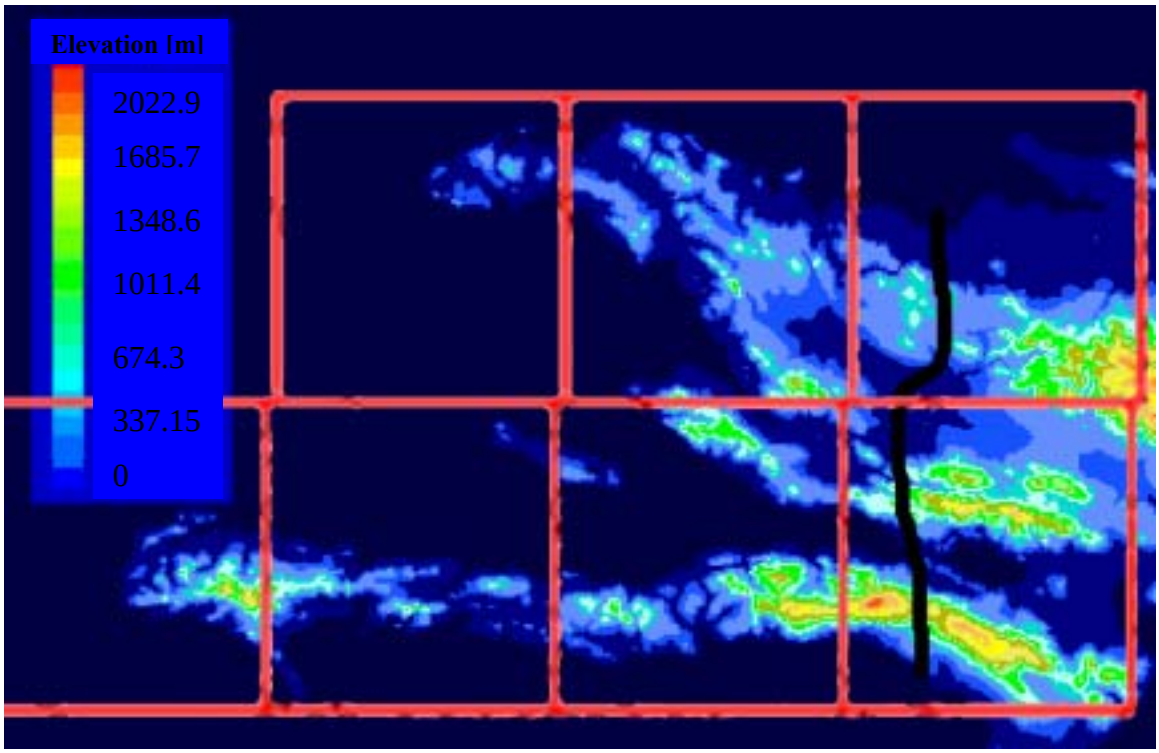


Figure 3-14. Haitian Topographical Map (Generated by GEOVU, Matlab, and TECPLOT using NOAA data)

Haiti's extreme topography in proximity to the ocean causes heavy cloud cover in the mountainous areas due to orographic lifting. Essentially, this is where the mountains physically force air to rapidly rise and cool. When the air cools enough to reach the dew point, clouds and precipitation occur. This phenomenon is verified by the increase of precipitation in the mountainous areas (Section 1.1.1). However, higher altitude can increase the amount of UV radiation incident to the surface by decreasing the atmospheric path (Acra, 1990). It will be assumed that any enhanced UV radiation due to altitude will be dwarfed by orographic lifting effects on average. Furthermore, temperatures can decrease greatly with altitude. For example, the village of Kenscoff at an elevation of 1,432 meters has an average temperature of 16 °C, while Port-au-Prince, at sea level, has an average temperature of 26 °C. These observations suggest that SODIS

could have limited effectiveness in the mountainous regions of Haiti but would need further research. Aside from how Haitian climate affects the water, the physical properties of the water, namely turbidity, are extremely important.

3.2 Turbidity

Turbidity measures the optical properties of liquids. Suspended particles can absorb and scatter light as it passes through. Consequently, highly turbid solutions can severely limit the amount of light penetration, thus reducing the efficiency of the SODIS process. For effective solar disinfection, waters should be less then 30 NTU (Nephelometric Turbidity Units) to ensure safe drinking water (SODIS News No. 3, August 1998). A practical method has been developed to assess water turbidity as it applies to SODIS. In the shade, the bottle is placed on top of the SODIS logo, and one looks from top to bottom. A legible logo means the water is less then 30 NTUs and an illegible logo means that the water is not initially suitable for solar disinfection (Figure 3-15).

Place Logo Under Bottle | Place Bottle in Sun (<30 NTUS) | Must Filter First (>30 NTUS)

Figure 3-15. Turbidity Assessment (EAWAG/SANDEC, Technical Notes)

When the water turbidity is higher than 30 NTUs, it must be treated by allowing coarse solids to settle for one day, inducing flocculation/sedimentation, or filtering.

3.3 SODIS Bottle Characteristics

PET (polyethylene terephthalate) bottles have emerged as the best SODIS container for several reasons, which will now be discussed.

3.3.1 PET Bottles

Plastic mineral water and soft drink bottles are gradually replacing glass. Plastic bottles are made of either PET or PVC (polyvinyl chloride). Both types of plastics contain UV-stabilizers to protect the material from UV radiation and oxidation. There is some concern, which needs further research, that some of these stabilizers may be a potential health risk. These additives are used much less in PET compared to PVC making PET the preferred SODIS material. PET is also a good transmitter of light in the UV and visible range. Simple comparison methods have been developed to determine whether a plastic material is PVC or PET. PVC has a distinct bluish gleam, which is especially noticeable around the edges. Additionally, PVC smells caustic when burned, whereas PET smells sweet (SODIS Technical Notes).

3.3.2 Water Depth

Another important characteristic of the PET bottles is they have an appropriate depth to make the SODIS process effective. Sommer *et al.* (1997) demonstrated that UV radiation is dramatically decreased by water depth. At a depth of 10 cm and a moderate turbidity level of 26 NTUs, UV-A radiation was decreased by 50%. The black bottom of the SODIS bottles induces a temperature gradient, which increases circulation. However, the

water depth should be less than 10 cm to ensure efficient disinfection, which is why bottles of less than 2 liters are typically used.

3.3.3 Transmittance Loss and Household Preference

SODIS bottles that are used daily and over long periods get scratched. This scratching leads to a reduction of UV transmittance and can decrease disinfection effectiveness over time. For these reasons, SODIS containers eventually have to be replaced. Consequently, PET bottles make the best choice as SODIS containers because they are usually the most locally available and are relatively inexpensive. The cost of PET bottles will be given more attention in the next section. Furthermore, field studies have shown the majority of people like the PET bottles because they are easy to handle, sturdy, and durable (SODIS News No. 3, 1998). In summary, PET Bottles have the following advantages and disadvantages (Table 3-4).

Table 3-4. Advantages and Disadvantages of PET Bottles

Advantages	Disadvantages
Inexpensive	Scratches and Aging Effects
Readily Available	Limited Heat Resistance (Slight deformation above 65 ° C)
Chemically Stable	
Transparent	
Most people like the bottles	
Low Weight	
Taste-neutral	
Relatively Unbreakable	

One of the most important aspects of any point of use technology is cost.

3.4 Economic Considerations

Willingness to pay is essentially demand driven and depends on the level of income and costs of the service provided. Access to good quality water in respect to its bacterial quality may not necessarily be considered an important need by every culture. Several severe diarrhea incidences per year may be regarded as “normal.” Thus, people may have a low desire to pay for water quality improvement.

Cost can be divided into initial capital, operation, and maintenance cost. Solar energy is free but bottles may have to be replaced due to aging and scratching. Replacement and initial investment in PET bottles may vary from country to country but usually amount to less than .5 US dollars per bottle. Typical Bottle costs are provided in Table 3-5.

Table 3-5. PET Bottle Cost in Different Countries (EAWAG/SANDEC, Technical Notes)

Country	Cost equivalent in US dollars
China	.14
Thailand	.3
Columbia	.4-.6
Indonesia	.07

The annual costs for a 5-person household would amount to about 3 US dollars. The full costs for SODIS should be borne by the user in order to achieve economic stability (Yayasan, 1997). This again brings up the most alluring aspect of this technology: the ability to produce disease free water at the household level for the cost of a plastic bottle. The social acceptance of this technology is extremely important, or it will never be applied.

3.5 Acceptance of SODIS

SODIS demonstration projects were carried out in seven countries by local intuitions to assess the socio-cultural acceptance of SODIS. The participating countries include: Columbia, Bolivia, Burkina Faso, Togo, Indonesia, Thailand, and China. A survey was then conducted to see how people felt about using SODIS to treat their water. The results are summarized by Table 3-6.

Table 3-6. Results of world SODIS survey (Environmental Concern, 1997)

I will Continue to use SODIS Survey				
Country	**Certainly**	**Maybe**	**Probably Not**	**Definitely Not**
Columbia	98	8	0	2
Bolivia	93	0	0	7
Burkina Faso	70	30	0	0
Togo	93	0	0	7
Indonesia	90	3	5	2
Thailand	97	0	0	3
China	55	45	0	0
Average	**84**	**12.6**	**.4**	**3**

This survey revealed that 84% of the users would definitely use SODIS in the future while 12.6% said they might use it in the future. When asked, villagers said the main reasons they would continue to use SODIS include:

- Easy and practical
- It provides good and clean drinking water
- Less work involved: (Not having to collect firewood for boiling etc.)
- No pathogens anymore, less sickness, less diarrhea, no stomachaches
- Save costs (fuel for boiling)
- Saves time
- Improves over quality of life

China and Burkina Faso had very high numbers answering maybe. Interviewees from China stated they would still drink water even though they are aware it is of low quality. Only 3% of the people said they would definitely not use SODIS again for the following reasons:

- No trust that bacteria could be killed by sunlight
- Time between preparation and consumption was too long
- Water taste like plastic (from the SODIS bags, not the PET bottles)
- Lack of materials

Overall, the results appear very positive with the majority of the villagers welcoming the SODIS technology.

The background for SODIS has been presented. The next section involves the materials and methods that were used to see if SODIS would work in Haiti.

Section III: Materials and Methods

4 Field Tests

To test the efficacy of SODIS in Haiti, the following measurements were made: sunlight intensity, bottle water temperature, and turbidity. These disinfection parameters were then coupled to microbial analysis, which consisted of presence-absence testing for total coliform, *E. coli*, and H_2S-producing bacteria.

4.1 Sunlight Intensity

Sunlight intensity was measured with the Kipp and Zonen Solrad kit (Figure 4-1).

Figure 4-1. Kipp and Zonen Solrad kit

This kit operates on the principle of converting light energy to heat, and heat into a quantifiable electric current. The effects of ambient temperature are automatically minimized and the measurements are considered independent of local climate. The protective glass dome filters in radiation between 350 – 1500 nm with a sensitivity of ± 5%. The field instrument was calibrated to ensure that the electrical current is

proportional to the watts per square meter incident to the ground. All of the user instructions were followed to guarantee the most accurate measurements possible.

4.2 Temperature

Water temperature measurements were made with three Enviro-Safe® thermometers. These thermometers contain a mixture of biodegradable citrus oil, and a green non-toxic dye, monoazo-anthroquinone. They are considered accurate to ± 1° C.

4.3 Turbidity

Turbidity measurements were made with a Hach Pocket Turbidimeter® (Figure 4-2).

Figure 4-2. Hach Pocket Turbidimeter®

This field instrument operates on the principle of the Nephelometric turbidity units (NTUs). The optical system includes an infrared light emitting diode (LED) and a detector to monitor scattered light. The LED emits light at 880 ± 20 nm, which is received by the light detector at 90° to the source of scattered light. The instruction manual was followed and the instrument was calibrated each day for quality control.

4.4 Microbial Presence Absence Tests

Presence absence tests do not quantify the amount of amount of bacteria. Instead, they answer the simple question of whether the target organisms are present or not. While it would have been useful to enumerate the amount of bacteria present, the most important question is: are there harmful bacteria present, and if so, can SODIS destroy all of them. For this reason, in addition to more simplistic testing procedures, presence absence test were run in parallel for total coliform, *E. coli*, and H_2S-producing bacteria.

4.4.1 Total Coliform and *E. coli*

Total coliform and *E. coli* were chosen as the main target organisms because of their accepted use to screen for pathogens (as described in section 2.6). Additionally, Acra *et al.* (1984) found that *E. coli* serve as a good indicator organisms for SODIS because they are more resistant to SODIS process when compared to other bacteria such as *P. aerugenosa*, *S. flexner, S. typh*, and *S. enteritidis.* Furthermore, Wegelin *et al.* (1994) found that *E. coli* maybe used as indicator organisms for SODIS and that the survival curves of different microorganisms are similar when exposed to sunlight. This implies that pathogens would die at close to the same rate as *E. coli.*

Total coliform and *E. coli* were simultaneously screened with Hach's Presence-Absence Broth, which contains bromcesol purple (BCP) for total coliform and methylumbelliferone glucuronide (MUG) for *E. coli*. BCP detects acid formation during the fermentation of lactose by coliform bacteria. The BCP reacts with the acid during 48

hours of incubation to turn the solution yellow, indicating the presence of coliform bacteria (Figure 4-3).

Figure 4-3. Negative (left) and Positive (right) results of total coliform BCP Test

E. coli is the only coliform to contain the enzyme β-glucuronidase which cleaves MUG , (Figure 4-4), to produce florescent byproducts.

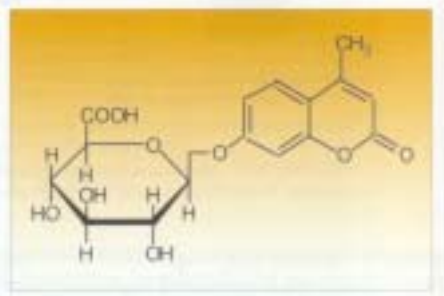


Figure 4-4. MUG (4-methylumbelliferyl-β-diblucuromide) (Maier *et al.*, 2000)

After 48 hrs of incubation, a long-wave ultraviolet lamp will cause bottles containing the cleaved MUG to fluoresce, indicating the presence of *E. coli* (Figure 4-4).

Figure 4-5. Negative (left) and Positive (right) results of *E. coli* MUG Test

The MUG medium is readily available from Hach and has been successfully used to analyze food and water for *E. coli* (Modberg, 1985; Feng and Hartman, 1982). However, Fujioka *et al.* (1988) and Hazen (1988) demonstrated that *E. coli* might be naturally present in waters that are without fecal contamination. Consequently, an additional test for microbial pathogens will also be used.

4.4.2 HACH PathoScreen™

Manja *et al.* (1982) observed that the presence of coliform bacteria is consistently associated with H_2S-producing bacteria. This indicates that H_2S-producing bacteria could be used to screen for fecal pathogens, which is advantageous in tropical regions because *E. coli* does not typically produce H_2S. Hach's PathoScreen™ detects the presence of H_2S-producing bacteria including *Salmonella, Citrobacter, Proteus, Edwardsiella,* some species *Klebsiella,* and other H_2S-producing bacteria. A more extensive list of H_2S

positive bacteria can be found in Farmer *et al.* (1985) and Brenner (1984). H_2S is first produced by the microorganism and it then complexes with iron in the PathoScreen^{TM} medium to produce a black solution as shown by Figure 4-6.

Figure 4-6. Negative (left) and Positive (right) results of H_2S PathoScreen^{TM} Test

There has been very good agreement in the literature between coliform and H_2S tests. Kasper *et al.* (1992) reported an 83% agreement between fecal coliform and H_2S tests, and a 96% agreement with total coliform. Martins *et al.* (1989) found no significant difference between hydrogen sulfide and coliform results. Additionally, Grant and Ziel (1996) found there to be as strong agreement between H_2S and coliforms tests. Finally, Kromoredjo & Fujioka (1991) concluded the H_2S test to be at least comparable if not superior to total coliform and *E. coli* test. Another major advantage of this test is it has a highly variable incubation temperature between 22 and 37 ° C while producing consistent results (Kasper *et al.*, 1992). This makes it possible to perform these tests without incubators in tropical regions. The composite testing for total coliform, *E. coli*, and

H_2S-producing bacteria should reveal the efficacy of SODIS in Haiti under various conditions. The precise experimental setup and procedure for making these measurements will now be described.

5 Experimental Setup and Procedure

5.1 Experimental Setup

Field Measurements were made on January 12th and 13th in Dumay, and from January 15th to the 21st in Santo. Nine 1.5 liter PET bottles were collected from a home, local garbage, and a local store. PET bottles were readily available in Santo. Black paint was applied to the bottom horizontal half of each of the bottle to enhance thermal effects. Several coats were required to ensure an opaque finish. During January 12th and 13th, six bottles were used. Three bottles were placed in the dark to serve as controls and three were left out in the sun for one day. From January 16th to the 21st, nine bottles were used to assess the effects of both one and two-day exposure. This bottle arrangement was divided into three groups with three bottles per group: 1-Day, 2-Day$_1$, and 2-Day$_2$. The temporal exposure arrangement of the nine bottles is given by Table 5-1.

Table 5-1. Bottle Exposure Arrangement for January 16th to 21st

Day number	1-Day	2-Day$_1$	2-Day$_2$
1	1-Day$_A$	2-Day$_{1\text{-}A}$	
	1-Day$_B$	2-Day$_{1\text{-}B}$	
	1-Day$_C$	2-Day$_{1\text{-}C}$	
2	1-Day$_A$	2-Day$_{1\text{-}A}$	2-Day$_{2\text{-}A}$
	1-Day$_B$	2-Day$_{1\text{-}B}$	2-Day$_{2\text{-}B}$
	1-Day$_C$	2-Day$_{1\text{-}C}$	2-Day$_{2\text{-}C}$
3	1-Day$_A$	2-Day$_{1\text{-}A}$	2-Day$_{2\text{-}A}$
	1-Day$_B$	2-Day$_{1\text{-}B}$	2-Day$_{2\text{-}B}$
	1-Day$_C$	2-Day$_{1\text{-}C}$	2-Day$_{2\text{-}C}$
4	1-Day$_A$	2-Day$_{1\text{-}A}$	2-Day$_{2\text{-}A}$
	1-Day$_B$	2-Day$_{1\text{-}B}$	2-Day$_{2\text{-}B}$
	1-Day$_C$	2-Day$_{1\text{-}C}$	2-Day$_{2\text{-}C}$
5	1-Day$_A$	2-Day$_{1\text{-}A}$	2-Day$_{2\text{-}A}$
	1-Day$_B$	2-Day$_{1\text{-}B}$	2-Day$_{2\text{-}B}$
…	1-Day$_C$	2-Day$_{1\text{-}C}$	2-Day$_{2\text{-}C}$

*The area of the encompassed by the dark brackets indicates exposure duration before microbial analysis.

This type of staggered arrangement allowed for the effects of both one and two day exposure to be measured every day. For example on Day 2, the 1-Day and 2-Day$_1$ groups are analyzed, while 1-Day and 2-Day$_2$ groups are tested the following day. The procedure for the actual measurements taken will now be discussed.

5.2 Experimental Procedure

Water was collected from various sources in the early morning using the SODIS bottles. Bottles were initially filled up about two-thirds and shaken vigorously for 30 seconds to provide aeration for photo-oxidative disinfection. They were then completely filled.

Additional samples were taken for raw water turbidity and microbial analysis. The Turbidimeter® was calibrated each day and every bottle was measured (six or nine bottles per day) at the beginning of each experiment. Total coliform, *E. coli*, and H_2S-producing bacteria tests were run in triplicate both before and after setting the bottles out in the sun. A blank was used for each type of test and every time a batch was run. All of the microbial samples were incubated in a cooler for two days prior to analysis. The incubation temperature was kept constant at 35 ° C using different proportions of hot and cold water. The 100 ml and 20 ml glass vials used for Hach's Presence-Absence Broth and PathoScreen™ respectively, were sterilized in boiling water for reuse.

The bottles were placed on a dark surface on top of a roof and where hourly sunlight intensity and bottle water temperature measurements where made (Figure 5-1).

Figure 5-1. A Typical Roof Top Experiment

Sunlight intensity measurements were taken so that the hourly averages are representative for each chronological hour. Hourly temperature measurements were simultaneously

made on three bottles and the thermometers were allowed to equilibrate with the bottle water temperature before readings were made. Most of the nights were spent completing the microbial analysis for the daily group of designated bottles. The results of these experiments will now be examined.

Section IV: Results and Discussion

6 Daily Results and Discussion

Field Measurements were made in Dumay on January 12th and 13th, and in Santo from January 15th to the 21st, 2001. Both Dumay and Santo are in Area 6 from Figure 3-1. For each day, the water source, turbidity measurement, sunlight intensity profile, temperature profile, and the corresponding microbial analysis will be presented and discussed.

6.1 Results for Water Collected on 01/12/01

Experiments were conducted on the roof of a building at the Dumay Mission for January 12th and 13th. On January 12th, water was collected from a heavily utilized local point source (Figure 6-1).

Figure 6-1. Water Source for 01/12/01

This water was very clear with an average turbidity of 1.3 ± .8 NTUs. The weather was warm and sunny with a few scattered clouds. It was 40 °C in the sun at noon and became slightly hazy towards the afternoon. Three bottles were placed in the dark for the duration of the experiment to serve as controls and three were placed in the sun at 10 A.M. The sunlight intensity profile, bottle water temperature profile, and corresponding thresholds are shown by Figure 6-2.

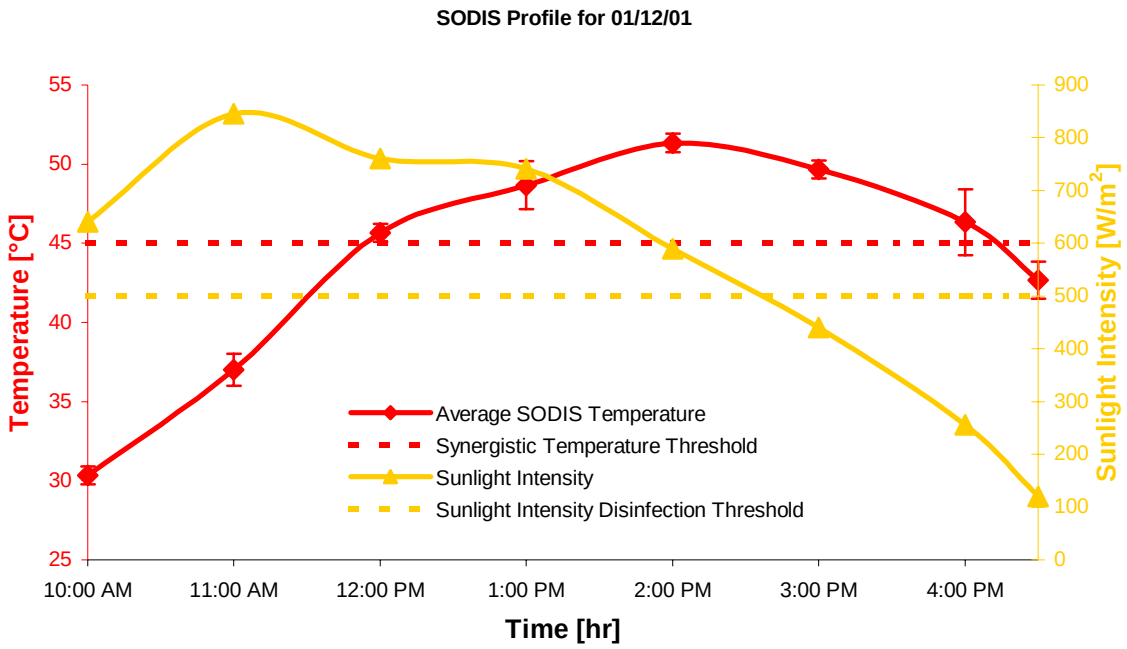


Figure 6-2. Sunlight Intensity, Average SODIS Bottle Temperature, and Corresponding Disinfection Thresholds for 01/12/01

The 5-hour average peak solar intensity was 715 W/m^2, which is well above the recommended disinfection threshold of 500 W/m^2 for 5 hours. The total amount of energy received from 10:00 A.M. to 5:00 P.M. was 4013 Wh/m^2. Bottle water temperatures surpassed the threshold of 45° C for 5 hours, indicating there would be synergistic thermal effects. These results suggest that conditions should be excellent for SODIS. The

corresponding microbial analysis for the raw, dark, and SODIS water is given by Table 6-1.

Table 6-1. Results of Microbial Analysis for Raw, Dark, and SODIS Water Collected on 01/12/01

		Total Coliform		*E. coli*		PathoScreen™	
Sample Type	**Sample Number**						
Raw	Raw 1	√		√		√	
	Raw 2	√		√		√	
	Raw 3	√		√		√	
Dark	1D	√		√		√	
	2D	√		√		√	
	3D	√		√		√	
Light	1L		√		√		√
	2L		√		√		√
	3L		√		√		√

The raw water tested positive for total coliform, *E. coli*, and H_2S-producing bacteria and the dark bottles had no distinguishable difference. However, the bottles that were exposed to the SODIS process tested negative for total coliform, *E. coli*, and H_2S-producing bacteria, indicating that all of the target organisms were completely inactivated by the SODIS process. This suggests that for these types of conditions, SODIS was extremely effective, producing a 100% kill rate for three different indicator organisms. Given the sunlight and temperature profile, these results are consistent with the literature. To test for possible bacterial regrowth, three 100 ml water samples were taken from the bottles exposed to the SODIS process to be reanalyzed on the final day.

6.2 Results for Water Collected on 01/13/01

Water was collected from an on-site spring well in Dumay (Figure 6-3).

Figure 6-3. On-Site water source for 01/13/01

This water had a low turbidity of 1.2 ± .6 NTUs. Three bottles were placed in the dark and three in the sun at 8 A.M. The morning was overcast with some haze, and black thunderclouds moved in around 11:30. The temperature was 28° C at noon and the sky cleared around 1:00 P.M. for an hour. Afterwards, it became cloudy again to produce a fluctuating sunshine and temperature profile shown by Figure 6-4.

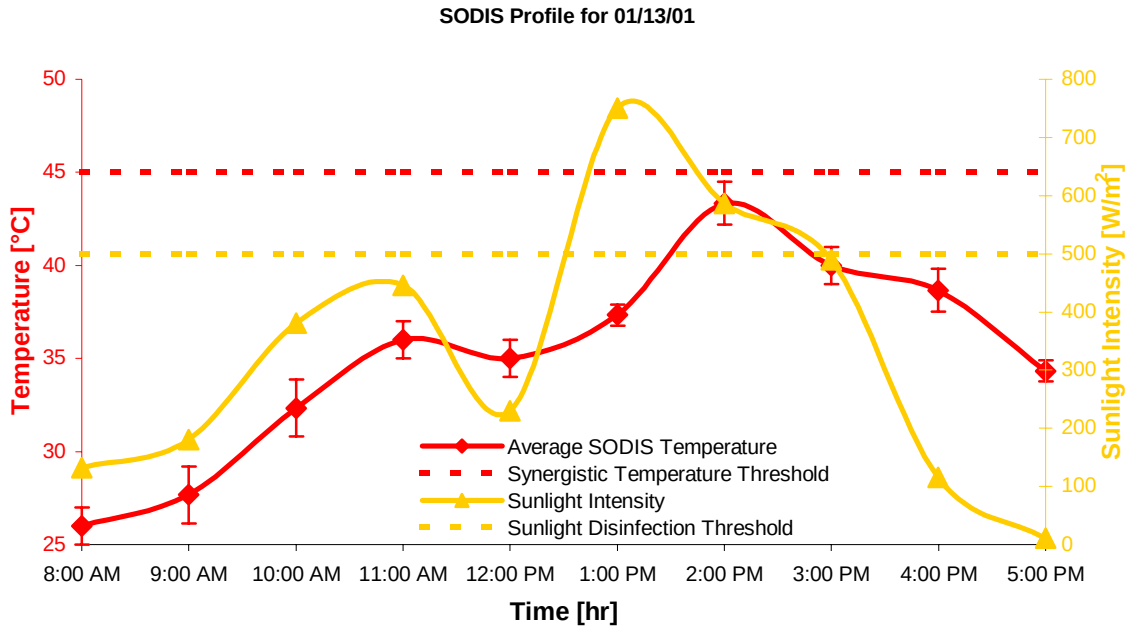


Figure 6-4. Sunlight Intensity, Average SODIS Bottle Temperature, and Corresponding Disinfection Thresholds for 01/13/01

The 5-hour average peak intensity was 530 W/m^2, and the total amount of energy measured from 8:00 A.M. to 5:00 P.M. was 3250 Wh/m^2. However, the 5-hour average peak intensity was largely raised because of the break through of sunshine around 1:00 P.M., and there were only 2 hours of sunlight intensity in excess of 500 W/m^2. The bottle water temperature never reached the synergistic threshold and these conditions are not considered favorable for SODIS. The resulting microbial analysis is given by Table 6-2.

Table 6-2. Results of Microbial Analysis for 01/13/01

		Total Coliform		*E. coli*		PathoScreen™	
Sample Type	**Sample Number**						
Raw	Raw 1	√		√		√	
	Raw 2	√		√		√	
	Raw 3	√		√		√	
Dark	1D	√		√		√	
	2D	√		√		√	
	3D	√		√		√	
Light	1L	√		√		√	
	2L	√		√		√	
	3L	√		√		√	

Every sample tested positive for all target organisms. The sunlight intensity never reached 500 W/m^2 for duration of 5 hours and the water temperature stayed below synergistic temperature threshold. Therefore, not all of the indicator organisms were inactivated for the bottles subjected to 1-day of the SODIS process. This implies that two consecutive days of exposure may be required for complete disinfection. Based on these results, the experimental methodology was shifted to incorporate the effects of 2-day exposure (as described in section 5-1). Dark bottle controls again agreed with the raw samples. Wegelin *et al.* (1994) found that the population of bacteria did not decrease in dark bottles during the course of the experiment. Consequently, these bottles, with an additional three, were used to investigate 2-day exposure. Furthermore, SODIS bottles were then placed on black plastic and tire pieces to help enhance thermal effects.

6.3 Results for Water Collected on 01/15/01

The previous day was spent packing lab equipment and moving to Santo. The tap water at this location was rumored to be undrinkable because of microbial contamination and was therefore put to the SODIS test. Turbidity was very low at 1.7 ± .6 NTUs. This water was extremely hard and produced a large amount of precipitate when boiled. The sky was covered with heavy black thunderclouds for almost the entire day, with a special guest appearance of the sun at around 11:00 A.M. When asked if this level of sunlight was typical, a Haitian villager responded, “No, never this dark” (Personal communication, 01/05/01). It was 27 °C at noon, and the following sunlight and temperature profile was observed (Figure 6-5).

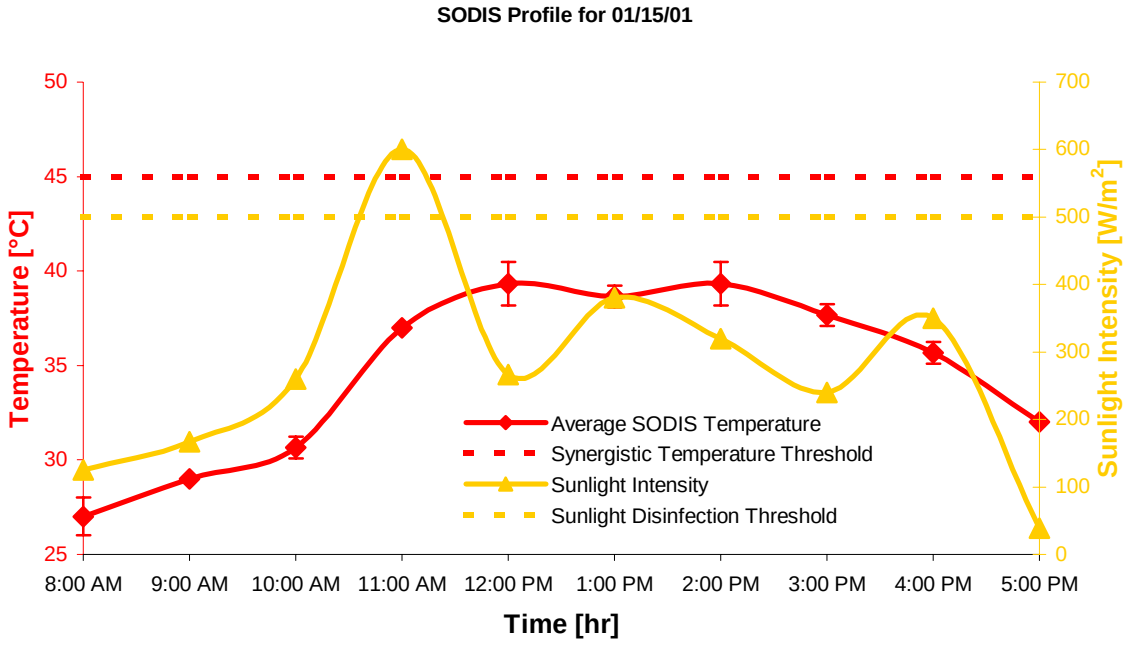


Figure 6-5. Sunlight Intensity, Average SODIS Bottle Temperature, and Corresponding Disinfection Thresholds for 01/15/01

The 5-hour average peak intensity was 383 W/m^2, and the total amount of energy measured from 8:00 A.M. to 5:00 P.M. was 2666 Wh/m^2. The bottle water temperature never reached the synergistic temperature and these conditions are poor for SODIS. The microbial analysis is given by Table 6-3. The results of the 2-day exposure are given with the results for the following day, as that day's sunlight and temperature conditions have an important influence on the outcome.

Table 6-3. Results of Microbial Analysis for 1-Day Exposure of Water Collected on 01/15/01

		Total Coliform		***E. coli***		**PathoScreen™**	
Sample Type	**Sample Number**						
Raw	Raw 1	√			√	√	
	Raw 2	√		√		√	
	Raw 3	√			√	√	
1-Day	1		√		√		√
	2	√		√			√
	3	√			√	√	

The raw water samples had relatively low bacterial concentrations. This was qualitatively deduced by observing that it took almost two full days of incubation to produce a small color change, and that two of the raw samples were negative for *E. coli*. This source was not be used again because of its low level of contamination. Regardless, the SODIS process was not 100% effective in destroying all of the tested organisms. This is in agreement with the results for 1/13/01, which had similar sunshine and temperature conditions. I suspect that if the raw water had higher bacterial concentrations, all of the samples would have tested positive because of the low sunshine and temperature levels.

6.4 Results for Water Collected on 01/16/01

Water was collected from a local spring well in Santo very similar to Figure 6-3. The water had a low turbidity of 1.1 ± .4 NTUs. The weather was hot and sunny with a few scattered clouds, and the noontime temperature was 40° C in the sun. The observed sunshine and temperature profile is given by Figure 6-6.

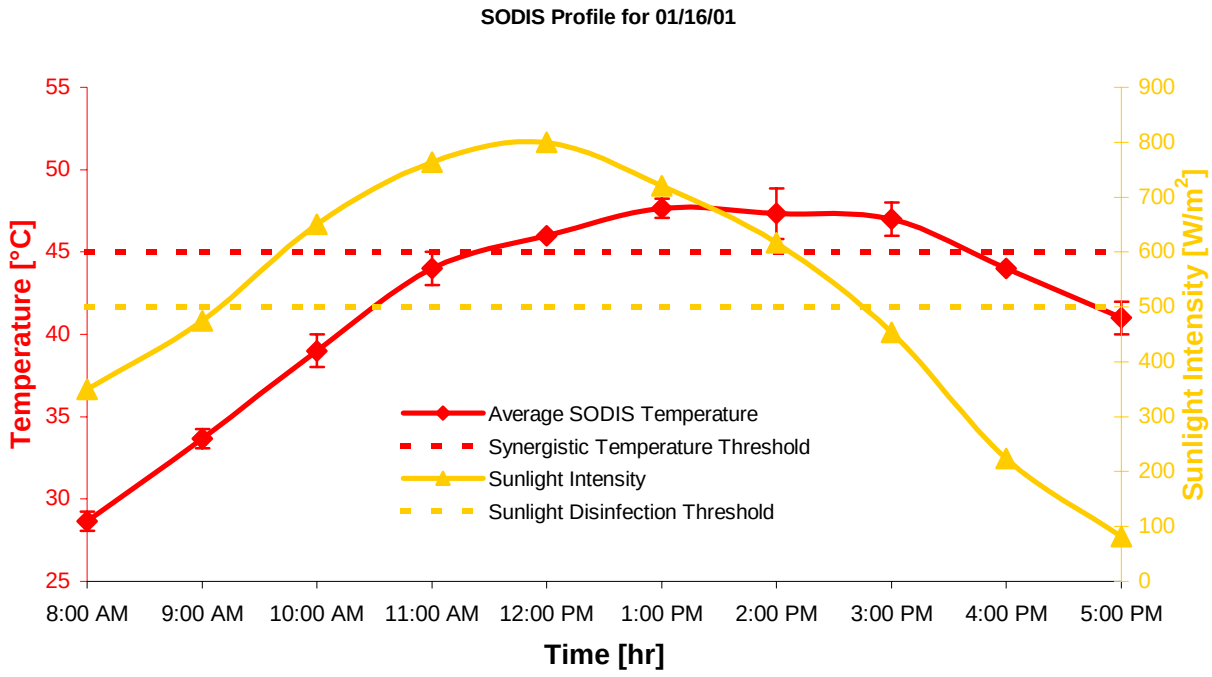


Figure 6-6. Sunlight Intensity, Average SODIS Bottle Temperature, and Corresponding Disinfection Thresholds for 01/16/01

The 5-hour average peak intensity was 710 W/m^2, and the total amount of energy received from 8:00 A.M. to 5:00 P.M. was 4920 Wh/m^2. The bottle water temperature surpassed the synergistic temperature for 4 hours and these conditions are considered very favorable for SODIS. The microbial analysis is given by Table 6-4.

Table 6-4. Results of Microbial Analysis for 1-Day Exposure of Water Collected on 01/16/01 and 2-Day Exposure of Water Collected on 01/15/01

		Total Coliform		*E. coli*		PathoScreen™	
Sample Type	**Sample Number**						
Raw	Raw 1	√		√		√	
	Raw 2	√		√		√	
	Raw 3	√		√		√	
1-Day	1		√		√		√
	2		√		√		√
	3		√		√		√
2-Day	1-A		√		√		√
(01/15/01)	1-B		√		√		√
	1-C		√		√		√

The disinfection parameters were met and all of the target organisms were inactivated by the SODIS process. Conclusions on the effects of 2-day exposure could not be made as 1-day exposure for 01/15/01 could have inactivated all of the organisms. However, 2-day exposure did have 100% inactivation as expected.

6.5 Results for Water Collected on 01/17/01

To simulate scenarios when Haitians would not have access to a designated potable water source, water with high bacterial concentrations was sought out. A puddle found by the side of the road was chosen and named “the festering pit” (Figure 6-7). Personal communication revealed that Haitians would never directly use a source such as “the festering pit” for potable water. However, I was told situations could arise when they

would take water of this quality and try to filter it. A Gift of Water Filter, (Figure 6-8), was used without chlorine to reduce the turbidity from 153 ± 6 NTUs to 23 ± 1.3 NTUs before being put to the SODIS test. For more information of the Gift of Water Filter, refer to Lantagne, 2001 and van Zyl, 2001.

Figure 6-7. "The Festering Pit" water source for 01/17/01

Figure 6-8. Gift of Water Filter

Raw water samples were taken after “the festering pit” water had passed through the filter to ensure no residual chlorine in the filter bucket would kill the bacteria. The day was hot and sunny with a noontime temperature of 38° C. Figure 6-9 shows the daily sunshine and temperature profile.

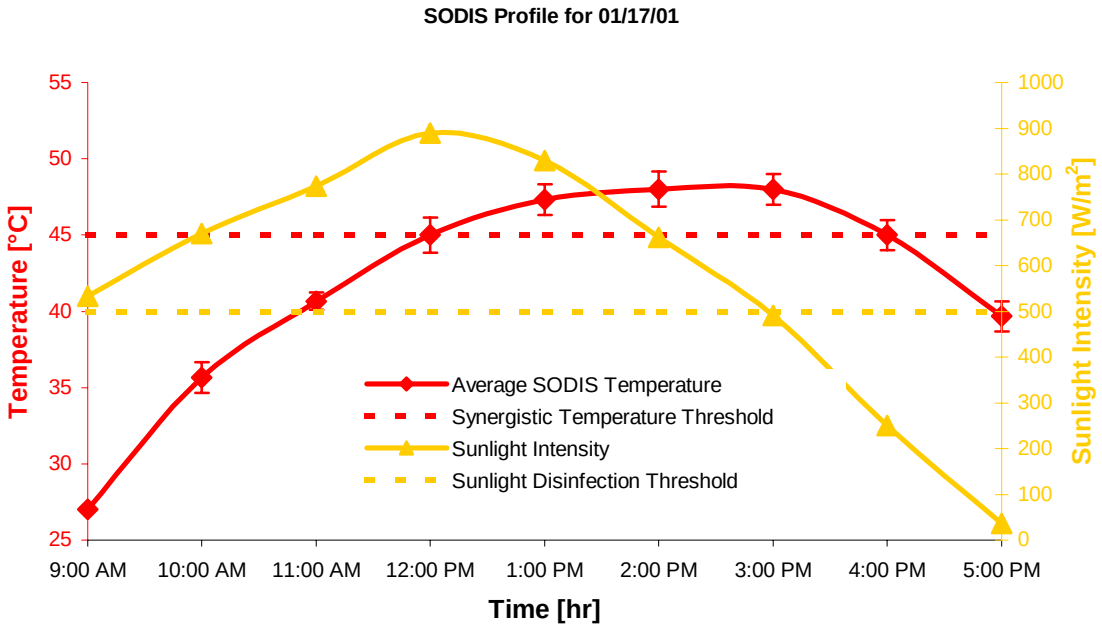


Figure 6-9. Sunlight Intensity, Average SODIS Bottle Temperature, and Corresponding Disinfection Thresholds for 01/17/01

The 5-hour average peak intensity was 765 W/m^2, and the total amount of energy received from 9:00 A.M. to 5:00 P.M. was 4851 Wh/m^2. The bottle water temperature reached the synergistic threshold for 5 hours producing favorable SODIS conditions. The coupled microbial analysis is given by Table 6-5.

Table 6-5. Results of Microbial Analysis for 1-Day Exposure of Water Collected on 01/17/01 and 2-Day Exposure of Water Collected on 01/16/01

		Total Coliform		*E. coli*		PathoScreen™	
Sample Type	**Sample Number**						
Raw	Raw 1	√		√		√	
	Raw 2	√		√		√	

	Raw 3	√		√		√	
1-Day	1		√		√		√
	2		√		√		√
	3		√		√		√
2-Day	2-A		√		√		√
(01/16/01)	2-B		√		√		√
	2-C		√		√		√

Contrary to expectation, the raw water results turned positive at comparable rates to previous water sources and produced similar color intensities. This suggests that the bacterial concentrations were not as high as hoped. The sunlight and temperature disinfection criteria was met and all the target organisms where inactivated. The effects of 2-day exposure could not be firmly concluded because all of the organisms could have been inactivated on 01/17/01, but the 2-day exposure still produced 100% disinfection.

6.6 Results for Water Collected on 01/18/01

After the disappointing bacterial concentrations produced by “the festering pit,” a search was undertaken for an even stronger source. Two goats, one cow, and a little boy were observed defecating in an irrigation stream, which was then selected for the SODIS test. Personal communication revealed that since the installment of local spring wells, this type of source was thankfully no longer required. The motivation for testing this type of source is if SODIS can work on water with large numbers of bacteria and high turbidity, it will certainly work on clearer water with lower microbial concentrations. The part of the irrigation stream sampled is shown by Figure 6-10.

Figure 6-10. Local Stream water source for 01/18/01

The stream was not as clear as the more realistic water sources previously sampled, and had a turbidity of 26 ± 3 NTUs. It had rained heavily for a brief period during the night, and runoff could have affected the stream's turbidity. The day was very sunny with a few clouds in the afternoon, and was slightly windier than past days. The noontime temperature in the sun was 37° C, and the corresponding sunlight and temperature profile is shown by Figure 6-11.

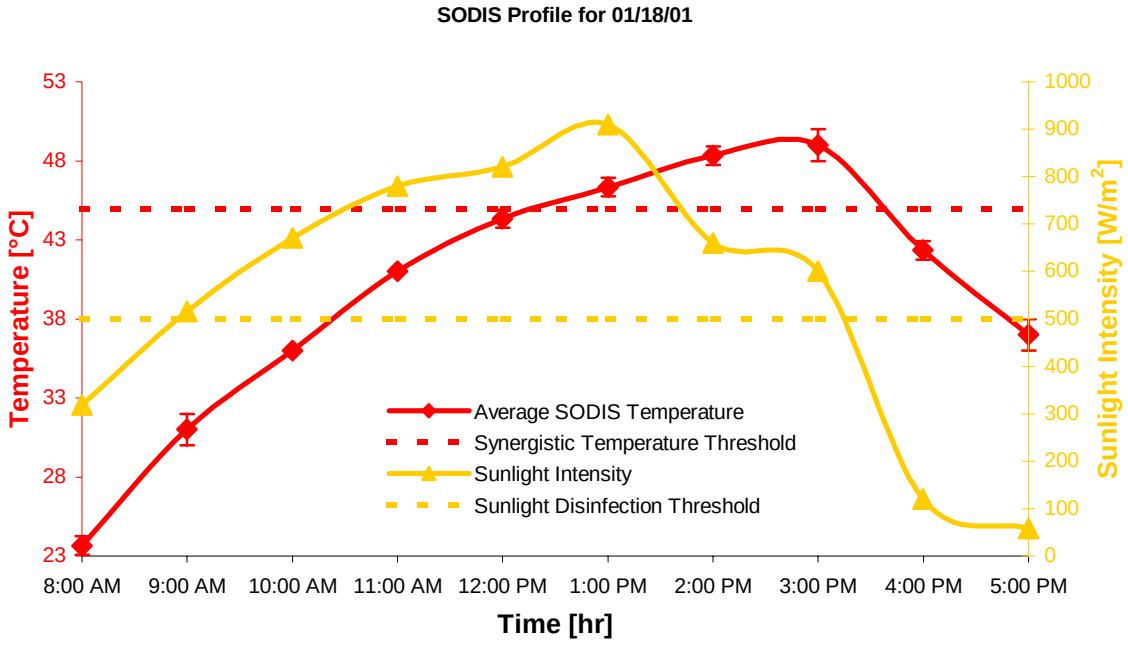


Figure 6-11. Sunlight Intensity, Average SODIS Bottle Temperature, and Corresponding Disinfection Thresholds for 01/18/01

The 5-hour average peak intensity was 768 W/m^2, and the total amount of energy received from 8:00 A.M. to 5:00 P.M. was 5265 Wh/m^2. The bottle water temperature was over the synergistic threshold for 3 hours, providing favorable SODIS conditions. The microbial analysis for 01/18/01 is given by Table 6-6.

Table 6-6. Results of Microbial Analysis for 1-Day Exposure of Water Collected on 01/18/01 and 2-Day Exposure of Water Collected on 01/17/01

		Total Coliform		*E. coli*		PathoScreen™	
Sample Type	**Sample Number**						
Raw	Raw 1	√		√		√	
	Raw 2	√		√		√	
	Raw 3	√		√		√	
1-Day	1	√		√			√
	2	√		√		√	
	3	√		√		√	
2-Day	1-A		√		√		√
(01/17/01)	1-B		√		√		√
	1-C		√		√		√

The raw water samples produced extremely strong positives in approximately 4 hours. The H_2S test turned so black, that the black ink labels on the bottle where no longer legible without first emptying the contents of the bottle. Furthermore, the coliform bacteria built up enough pressure by gas production, that the 100 ml bottles exploded almost their entire contents when opened. After my first shower, the remaining bottles were opened inside a garbage bag. This confirmed that the irrigation stream indeed had high bacterial concentrations. In fact, despite the favorable SODIS conditions of over 7 hours of sunshine in excess of 500 W/m^2, a 5-hour average peak intensity was 768 W/m^2, and 3 hours above the synergistic temperature, almost all of the 1-day samples still gave weak positive results. This result is attributed to the high initial amount of bacteria present. The 2-day samples from 01/17/01 were all negative but the microbes could have easily been completely inactivated on either day. It was also observed that the water temperatures seemed slightly low, given the amount of sunshine received. This could be

because the initial temperature was slightly colder than normal at 23 °C compared to the typical 26 °C. Additionally, the slight increase in wind could have caused some convective cooling effects.

6.7 Results for Water Collected on 01/19/01

Water was again collected from the irrigation stream because of its high bacterial concentrations. The turbidity was much lower than the previous day at 7 ± .8 NTUs, which could be explained by the lack of rain. The day was mostly sunny with a few scattered clouds and it was very windy. A noontime air temperature of 38 °C was observed, and the day's sunshine and temperature profile is given by Figure 6-12.

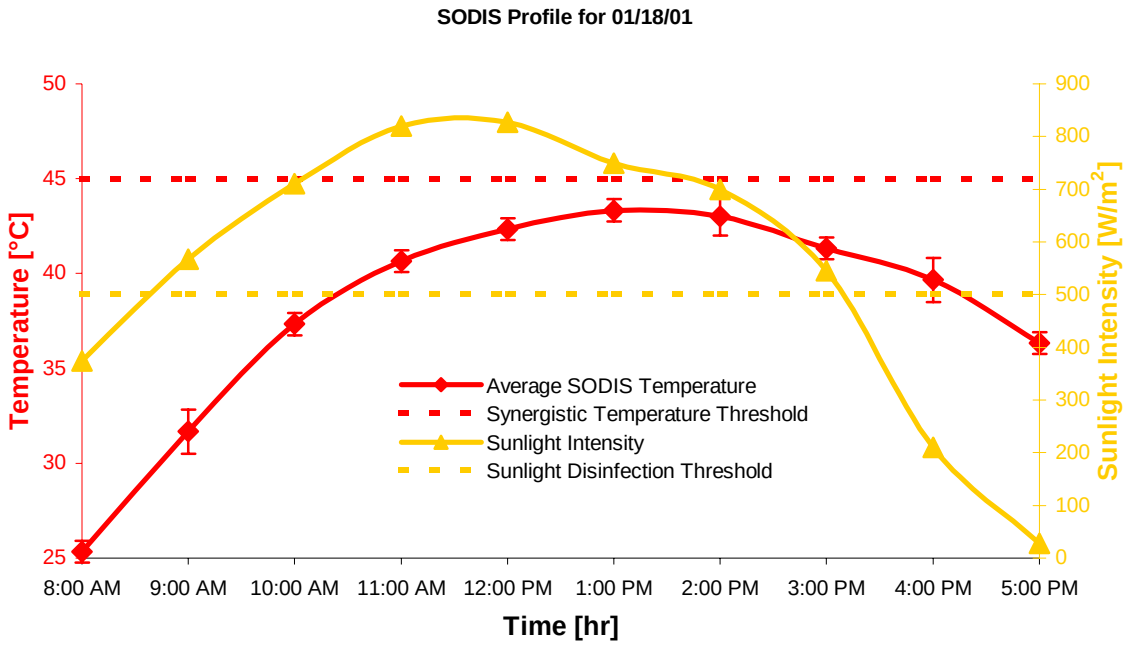


Figure 6-12. Sunlight Intensity, Average SODIS Bottle Temperature, and Corresponding Disinfection Thresholds for 01/19/01

The 5-hour average peak intensity was 761 W/m^2, and the total amount of energy received from 8:00 A.M. to 5:00 P.M. was 5330 Wh/m^2. The bottle water temperature never surpassed the synergistic threshold despite the large amount of sunshine and fairly warm ambient temperatures. The microbial analysis is given by Table 6-4.

Table 6-7. Results of Microbial Analysis for 1-Day Exposure of Water Collected on 01/19/01 and 2-Day Exposure of Water Collected on 01/18/01

		Total Coliform		*E. coli*		PathoScreen™	
Sample Type	**Sample Number**						
Raw	Raw 1	√		√		√	
	Raw 2	√		√		√	
	Raw 3	√		√		√	
1-Day	1	√		√		√	
	2		√		√		√
	3	√		√		√	
2-Day	2-A		√		√		√
(01/18/01)	2-B		√		√		√
	2-C		√		√		√

The raw water samples again exhibited the same strong positives as they did on 01/18/01. This day received 7 hours of sunshine over the recommended threshold and had a relatively high 5-hour average peak intensity. However, two-thirds of the samples tested weakly positive for all of the target organisms. This is most likely a result of the high initial amount of bacteria and the fact that the bottles never reached the synergistic temperature threshold. Bottle temperatures were probably suppressed by the convective cooling effects of this day's strong wind. An important result is that the 2-day samples all

tested negative, while the samples from 1-day exposure for both days still had target bacteria present. This clearly shows that 2 days of exposure produce superior bacterial inactivation when compared to 1 day of the SODIS process.

6.8 Results for Water Collected on 01/20/01

Water was collected for the last time at the irrigation stream. The water had a turbidity of 13.2 ± 3.8 NTUs. The day was partly cloudy and the temperature in the sun was 38 °C at noon. High winds were again observed. This time a board was placed near the bottles to shelter them from any convective cooling effects, but not so close that it would cast a shadow on the bottles. The sunlight and temperature profile is shown by Figure 6-13.

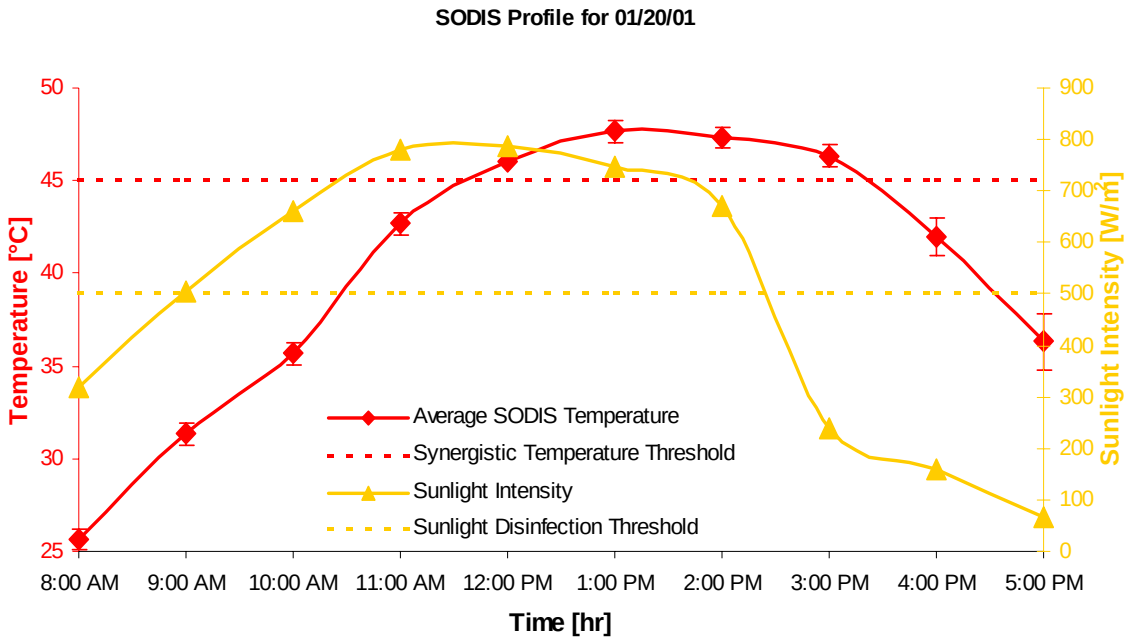


Figure 6-13. Sunlight Intensity, Average SODIS Bottle Temperature, and Corresponding Disinfection Thresholds for 01/20/01

The 5-hour average peak intensity was 729 W/m^2, and the total amount of energy received from 8:00 A.M. to 5:00 P.M. was 4742 Wh/m^2. The bottle water temperature surpassed the synergistic temperature for 4 hours. An important observation is that the bottle temperatures did reach the synergistic temperature threshold for over 4 hours despite having strong winds similar to the previous day. Furthermore, this day had a lower 5-hour average peak intensity, 729 W/m^2, than on 01/19/01, 761 W/m^2. Comparatively between these two days, the ambient temperatures were about the same, 01/20/01 received less sunshine, and 01/20/01 had higher bottle water temperatures because of the difference in wind. This suggests that blocking convective cooling may be an important aspect of SODIS in windy conditions. The microbial analysis for 01/20/01 is given by Table 6-8.

Table 6-8. Results of Microbial Analysis for 1-Day Exposure of Water Collected on 01/20/01 and 2-Day Exposure of Water Collected on 01/19/01

		Total Coliform		*E. coli*		PathoScreen™	
Sample Type	**Sample Number**						
Raw	Raw 1	√		√		√	
	Raw 2	√		√		√	
	Raw 3	√		√		√	
1-Day	1		√		√		√
	2	√		√		√	
	3	√		√		√	
2-Day	1-A		√		√		√
(01/19/01)	1-B		√		√		√
	1-C		√		√		√

The raw water had the same high concentrations of bacteria as described on 01/18/01. Favorable conditions were once again dwarfed by the high initial concentrations of bacteria and two-thirds of the 1-day samples tested weakly positive for all the target organisms. The 2-day exposure again had a 100% kill rate while the 1-day exposures achieved only 66% inactivation.

6.9 Results for 01/21/01

The 2-day bottles from 01/20/01 were placed outside again on 01/21/01. The day started out very sunny but heavy clouds appeared for an hour around 1:00 P.M. The noontime temperature was 38 °C in the sun. The following sunlight and temperature profile was produced (Figure 6-14).

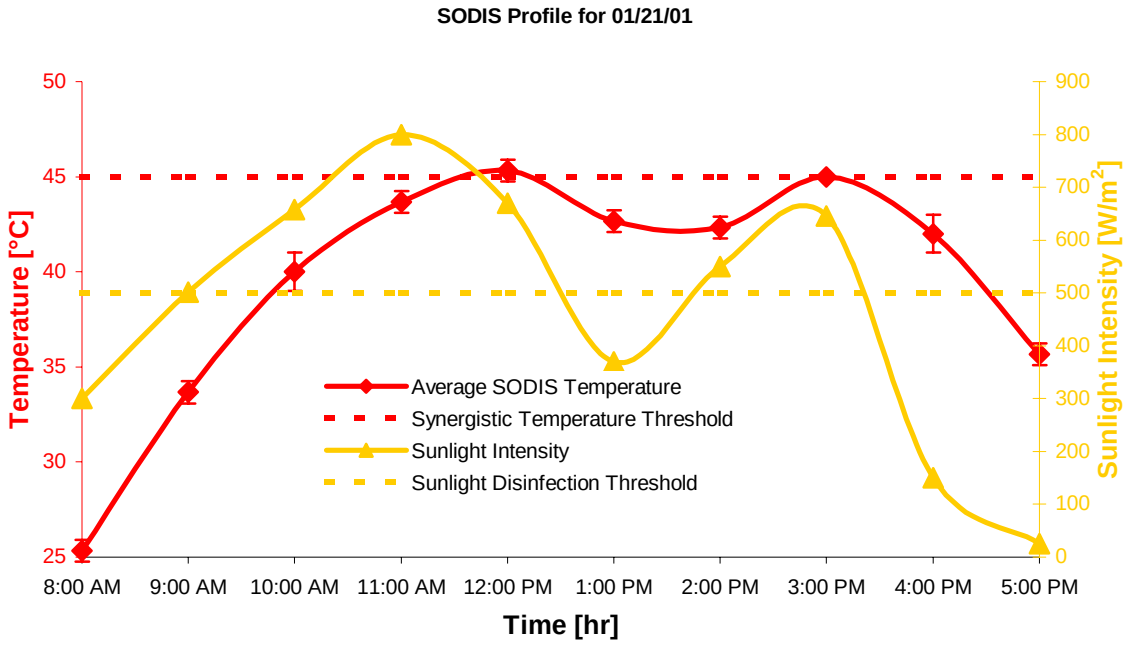


Figure 6-14. Sunlight Intensity, Average SODIS Bottle Temperature, and Corresponding Disinfection Thresholds for 01/21/01

The 5-hour average peak intensity was 664 W/m^2, and the total amount of energy received from 8:00 A.M. to 5:00 P.M. was 4509 Wh/m^2. The bottle water temperature reached the synergistic temperature for 2-nonconsecutive hours. The microbial analysis of the bottles testing for bacterial regrowth from 01/12/01 is also given by Table 6-9.

Table 6-9. Results of Microbial Analysis 2-Day Exposure of Water Collected on 01/19/01 and for Bacterial Regrowth from water on 01/12/01

		Total Coliform		*E. coli*		PathoScreen™	
Sample Type	**Sample Number**						
2-Day	2-A		√		√	**NA**	**NA**
(01/20/01)	2-B		√		√		√
	2-C		√		√		√
Regrowth	1		√		√		√
(01/12/01)	2		√		√		√
	3		√		√		√

Consistent with previous 2-day exposures, 100% inactivation was achieved. Sample 2-Day$_{2\text{-}A}$ for the H_2S-producing bacteria was disregarded, as the cap for the 20 ml vial was broken. No bacterial regrowth was observed for any of the target organisms, which is consistent with the results found by Wegelin (1994).

7 Summary of Results and Discussion

The general results for turbidity, sunlight intensity, how the measured and modeled sunlight intensity compared, and the overall microbial analysis will be presented. These results and what they imply for SODIS in Haiti will then be discussed.

7.1 Summary of Results

7.1.1 Turbidity

All realistic water sources were very clear with an average turbidity of 1.3 ± .6 NTUs. This is consistent with Lantagne (2001), who found an average turbidity of .88 ± .84 NTUs collected from several other places in Haiti.

7.1.2 Sunshine and Temperature

The average sunshine intensity and temperature profile for all days, January 12th through January 21st, 2001 is given by Figure 7-1.

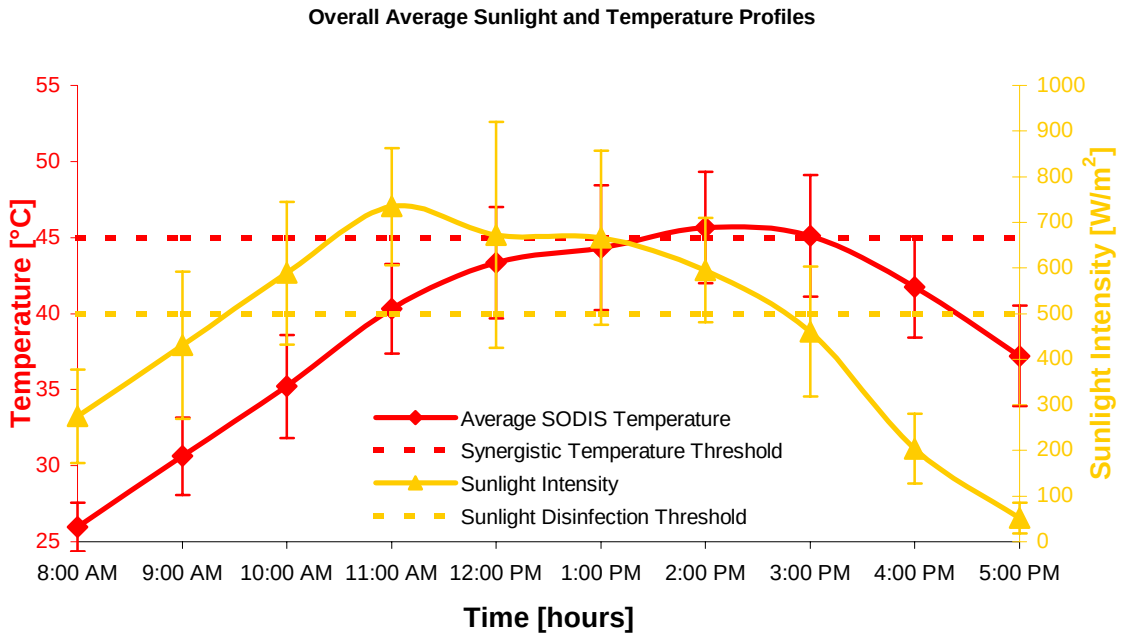


Figure 7-1. Average Sunlight and Bottle Water Temperature observed in Haiti during January

The 5-hour average peak intensity was 651 W/m^2, and the average total amount of daily energy received was 4537 Wh/m^2. On average, the bottle water temperature hovered around the synergistic temperature for about 3 hours.

Two of the nine days were under the cover of thunderclouds and had sunlight and temperature profile shown by Figure 7-2.

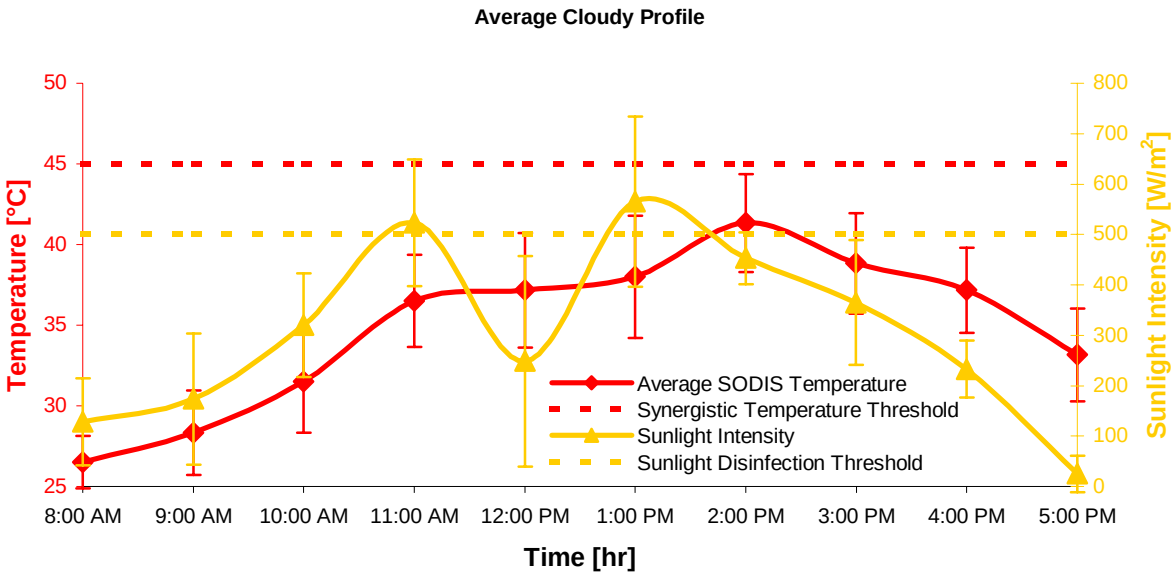


Figure 7-2. Average Stormy Day Profile Observed for the 13th and 15th of January (2 of 9 days)

For these two stormy days, the 5-hour average peak intensity was 445 W/m^2, and the total amount of energy received was 2958 Wh/m^2. The bottle water temperature never reached the synergistic threshold.

Subtracting these two stormy days from the rest paints a better picture of a typical day of Haitian sunshine and bottle water temperature. This can be seen in Figure 7-3 by the decrease in the size of the error bars when compared to Figures 7-1 and 7-2.

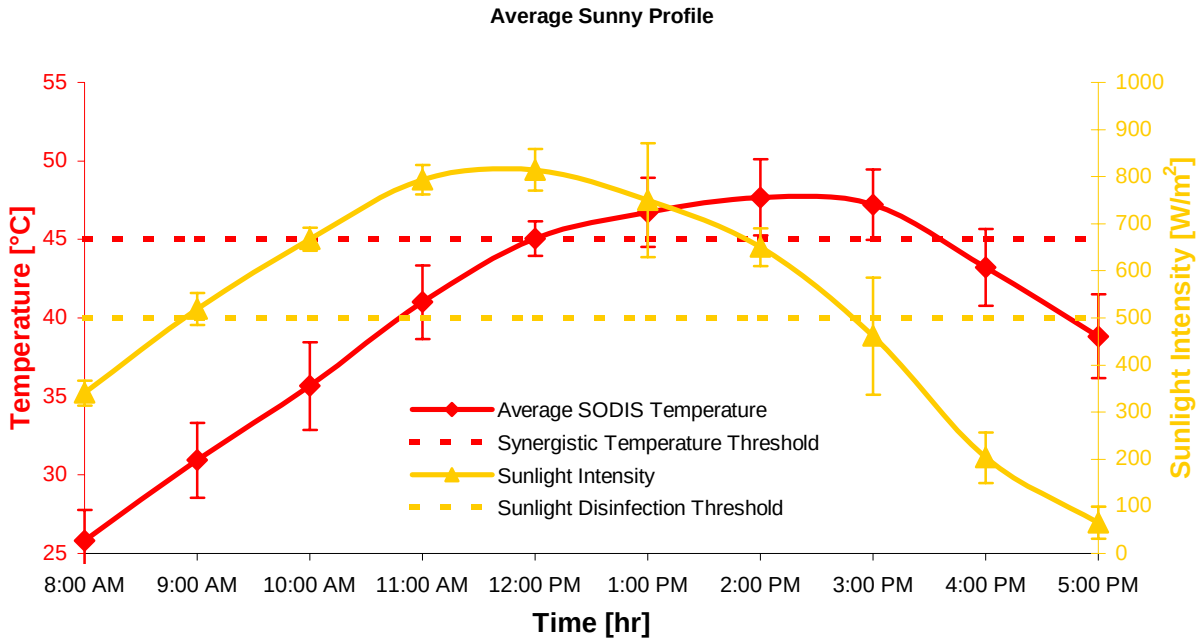


Figure 7-3. Average Non-Stormy Day Profile for Partly Cloudy to Mostly Sunny days (7 of 9).

For the average of the non-stormy days, the 5-hour average peak intensity was 735 W/m^2, and the total amount of energy received was 5061Wh/m^2. The bottle water temperature rose past the synergistic threshold for 4 hours.

7.1.3 Measured Intensity Comparison to Model Prediction

The sunlight intensity measurements were made in Area 6 from Figure 3-1. The measured average, minimum, and maximum 5-hour peak intensity values will be compared to the simulated values in January for Area 6 (Table 7-1).

Table 7-1. Comparison between Simulated and Observed Average, Minimum, and Maximum 5-hour Average Peak Intensity Values.

	Simulated (W/m^2)	Observed (W/m^2)	Percent Agreement
Average	641	651	98.5 %
Minimum	615	383	62.3 %
Maximum	660	768	86.0 %

The simulated and measured average values are in excellent agreement. However, the maximum and minimum are significantly different. The reason for this disagreement becomes apparent when looking at the measured minimum and maximum daily total energies compared to the 10-year average values obtained from NASA. The measured minimum day had a measured total energy value of 2666 Wh/m^2. This value was roughly adjusted to 2800 Wh/m^2 to compensate for the period between 6:00 A.M. and 8:00 A.M when there was sunshine but no measurements. Similarly, the maximum intensity was adjusted from 5265 Wh/m^2 to 5600 Wh/m^2 to compensate for the missed sunlight between 6:00 A.M. to 8:00 A.M. A comparison of percent agreement between the two total energy values along with the intensity values is given by Table 7-2.

Table 7-2. Percent Agreement between Simulated and Observed Intensity Values, and Observed and NASA 10-year Average Total Energy Values for the Maximum and Minimum Energy in January

	Simulated (W/m^2)	Observed (W/m^2)	Intensity Percent Agreement	Observed Total Energy (Wh/m^2)	Total Energy Provided by NASA (Wh/m^2)	Total Energy Percent Agreement
Minimum	615	383	**62.3 %**	2800	4490	**62.4 %**
Maximum	660	768	**86.0 %**	5600	4960	**88.6 %**

The difference in total energy adequately explains the difference in intensity because they are so intimately related. To verify this, the observed minimum total energy value is plugged into the model and it produces a 5-hour average peak intensity value of 385

W/m^2. This minimum average intensity is in over 99% agreement with the observed value of 383 W/m^2. The maximum observed value produces a 5-hour average peak intensity of 770 W/m^2, which is in over 99% agreement with the observed maximum value of 768 W/m^2. It then follows that the discrepancy between the simulated and observed minimum and maximum results can be explained by the total energy values provided by NASA. The reported minimum and maximum NASA total energies are likely different from the measured values because they are representative of a 10-year average for a degree latitude and longitude quantity. However, the measured amounts are at a much smaller scale within that averaged area making them more susceptible to local fluctuations.

7.1.4 Overall Microbial Analysis

Microbial testing was conducted using total coliform, *E. coli*, and H_2S-producing bacteria to assess how SODIS performed under various conditions. The total results for the raw water, 1-day exposure, and 2-day exposure are given by Table 7-3.

Table 7-3. Overall Microbial Analysis

Initial Raw Contamination %, (Positive/Sampled)	**1-Day Kill** %, (Negative/Sampled)	**2-Day Kill** %, (Negative/Sampled)
97.2%, (70/72)	**52.8%, (38/72)**	**100%, (53/53)**

The three types of microbial tests showed good agreement between one another for both positive and negative results for all tests made (Table 7-4).

Table 7-4. Percent Agreement between Different Microbial Tests

Type of Agreement	Total Coliform and *E. coli*	Total Coliform and H_2S Bacteria	*E. coli* and H_2S Bacteria
Positive	92.7 %	95.1 %	97.4 %
Negative	91.2 %	96.9 %	94.1 %

The different tests were in strong agreement indicating the raw water had all of the target organisms present and that the SODIS process had roughly the same effect on the different types of indicator bacteria.

7.2 Discussion

Every point source that people used for potable water in Dumay and Santo had very low turbidity. Lantagne (2001) sampled several other locations in Haiti to find that they all had minimal turbidity. Based on the measurements made in January, it would be reasonable to say that most places would not need a prefiltration step and SODIS could be directly applied. However, to make a broader conclusion, additional samples would have to be taken in the rainy seasons (around October and May) to investigate how increased runoff would affect turbidity.

The intense Haitian sunshine and warm climate appear to provide conditions suitable for effective SODIS. This research was conducted during Haiti's winter, implying shorter and colder days compared to most of the year. However, "the rainy months like October and May, could receive less sunshine, but you could easily count the days on your fingers in Haiti that receive no sunshine because they are so few" (Nathan Dieudonne, personal communication, 1/14/01). It would be important to conduct further SODIS testing around

October when there is less sunshine and increased cloudiness. The highly heterogeneous nature of Haiti's climate makes general conclusions difficult to formulate. At higher altitudes, the orographic enhanced cloud cover and the colder temperatures could compromise the effectiveness of SODIS. If the mountainous regions are too cold to realistically incorporate synergistic thermal effects, the bottles should not be painted black and could be placed in solar reflectors. This would have the SODIS process rely solely on optical inactivation, which could be very effective given there is more UV radiation at higher altitudes. If this technique were ineffective, an alternative disinfection method would have to be used in the mountainous regions.

The mathematical sunshine model proved to be very accurate in predicting the 5-hour average peak sunshine intensity for a given total energy value. However, caution should be used when applying the NASA values obtained for the 10-year average of the average, minimum, and maximum total daily energy. The average monthly values are regarded as more accurate because they sample around 30 or 31 days per month, and that average is then averaged over the span of 10 years. However, measurements for the minimum and maximum energies are a single value for each month, and their average comes from a much smaller sample population. More importantly, the NASA values are assumed accurate for what they represent, but their spatial resolution does not capture the presence of microclimates within a degree longitude and latitude. This can cause inaccurate predictions for specific locations within highly heterogeneous areas smaller than a degree longitude and latitude. However, simulated values would likely be much more accurate for specific locations in a homogeneous site. The mathematical model that was presented is a valuable tool to obtain a first approximation if SODIS would be applicable for Haiti

throughout the year. This method of sunshine simulation could easily be applied to estimate the year-round SODIS effectiveness anywhere else in the world. One would only need to obtain the locations latitude and total energy values from a source such as NASA. If the sunlight intensities appear adequate for a location, then physical tests should be conducted to evaluate the success of SODIS.

SODIS efficacy was evaluated by the inactivation of total coliform, *E. coli*, and H_2S-producing bacteria. The results verify that Haiti does have water problems with microbial contamination as 97% of the samples tested positive for all indicator organisms. Impacts of exposure duration varied significantly between 1-day and 2-day periods. Under various sunshine intensities, bottle water temperatures, and initial bacterial concentrations, 1-day exposure completely inactivated all of the bacteria half of the time, while the 2-day exposure period achieved 100% inactivation for all conditions experienced. A major drawback of this study is two consecutive stormy days such as on 01/15/01 were not observed and SODIS efficacy for these conditions in Haiti is unknown.

Guidelines that differentiate between 1-day and 2-day exposure have been suggested in the literature. However, it is considered more practical to have every bottle exposed for a 2-day duration. It was observed that 100% bacteriological inactivation is mainly a function on sunlight, temperature, and initial microbial concentration (the effects of turbidity and wind are considered less important for Haiti). These parameters are highly variable and the right conditions for 100% inactivation with 1-day exposure were only met half of the time. To ask a villager to gauge how much sunshine a specific day has

received takes away from the simplistic beauty of this technology. First, it is distracting for villagers to have to constantly think about how much sunshine a bottle is receiving. Second, this judgment is prone to large errors (I met a man who told me he was 177 years old), which could ultimately cause illness or death. If the 2-day exposure results that were observed in January hold true, leaving every bottle out in the sun for 2-day exposure would take the guess work out of this technology and would always lean towards the conservative side of disinfection. A practical way of providing people with cold water every morning that has undergone a 2-day exposure period can be termed “a SODIS triangle.” Essentially, it consists of three groups of bottles that are rotated every morning, so two groups are out in the sun and one is being used for consumption. This process is illustrated in detail in the next section. From the experiences and the results produced in Haiti, a set of practical application guidelines has been constructed.

Section V: Practical Application Guidelines

The SODIS disinfection process is simple to apply but would require training at the community level to ensure optimal benefits. These guidelines are a product of what was experienced in Haiti along with some adaptations from the SODIS Technical Notes (EAWAG/SANDEC), and should be applied to those areas deemed suitable for SODIS.

8 Practical SODIS Procedure

8.1 Bottles

Collect Clear PET bottles from home or local market of 1-2 liters. Enough should be obtained to sustain a household level of consumption. PET bottles can be easily identified as they will say PET on the bottom or they main contain the following symbol: 

Make sure the bottles are not to scratched up so light can easily penetrate.

Make sure the bottles do not leak and have caps that seal watertight.

All labels should be removed and both the inside and outside of the bottles should be washed to ensure optimal light transmittance.

Paint half of the bottles black (if paint is available): 

- The side with any residual label glue should be painted. This eliminates the hassle of trying to remove it and prevents future dirt build up, which would reduce light transmittance.
- Use as many paint coats as necessary to create an opaque finish.
- Hold the bottle up to light and make sure light does not come through the bottom.

8.2 Water

Water should be obtained from a common village supply: well, stream, pond, reservoir, etc.

Water must be clear enough for SODIS to work. Turbidity can be checked by placing a copy of the SODIS logo under the bottle and checking its readability.

Place logo under a bottle

Put in sun (<30 NTUs)


Have to filter or let settle until logo is legible (>30 NTUs)

If the logo is legible, then turbidity is low enough for SODIS. If not, the water must be left to settle or processed with a filter if available.

When collecting water, rinse the outside of the bottle to remove any buildup that would block sunlight transmission

Fill the SODIS bottles about two-thirds full and screw on the cap. Shake the bottles vigorously for about 20 seconds to ensure the water is sufficiently oxygenated. The bottles are now ready for exposure.

8.3 Exposure

An area must be chosen that receives sunshine throughout the entire day.

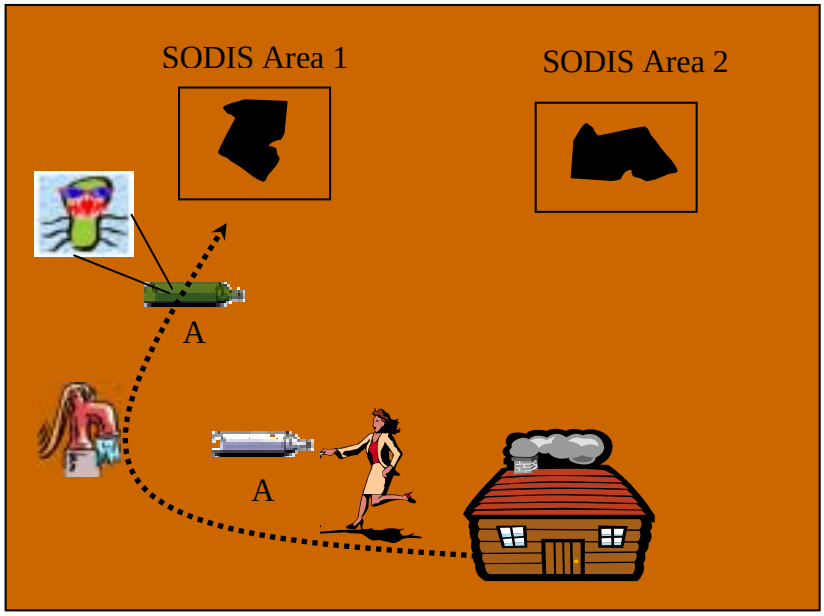
Place bottles on dark surfaces to enhance thermal inactivation such as black plastic or tire pieces, which appear to be ubiquitous in Haitian garbage. Corrugated metal rooftops reach high temperatures and they would be excellent SODIS areas if they receive full sunshine during the day.

Bottles should be sheltered from high winds, if the occasion calls for it, to decrease thermal depletion by convection (wind blowing the heat away from the bottles). Make sure that any objects use to shelter wind do not shelter sunshine.

To make things simple, routine, and conservative, groups of bottles should be set out for two days, regardless of the weather conditions. This takes out the guesswork as to the whether conditions are right for SODIS. A practical approach to this exposure guideline would be to set up a "SODIS Triangle." This involves three groups of bottles: A, B, and C; and two designated SODIS areas: SODIS Area 1 and SODIS Area 2. The two areas could simply be adjacent spots on a roof. The SODIS Triangle is set up as follows:

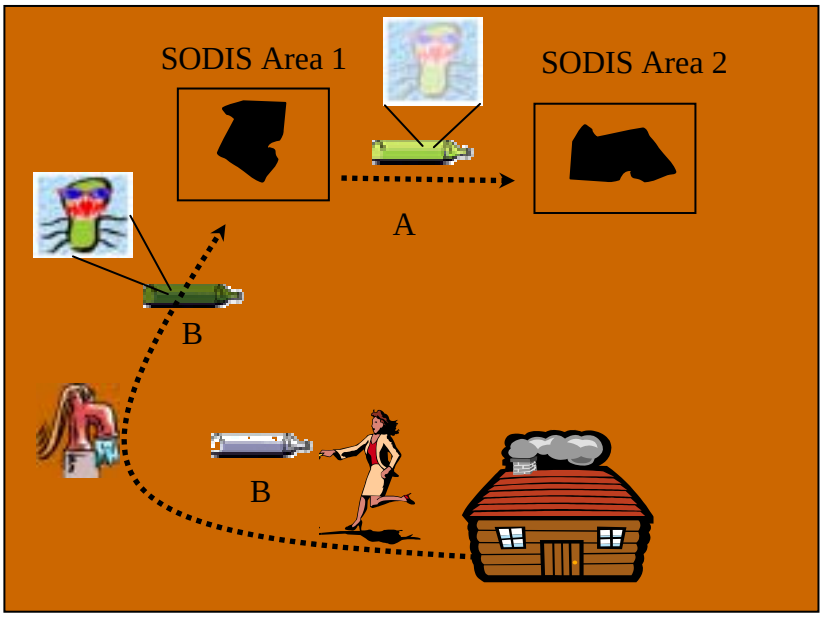
Morning of Day 1:

- Collect water with group A
- Place bottle group A in SODIS Area 1



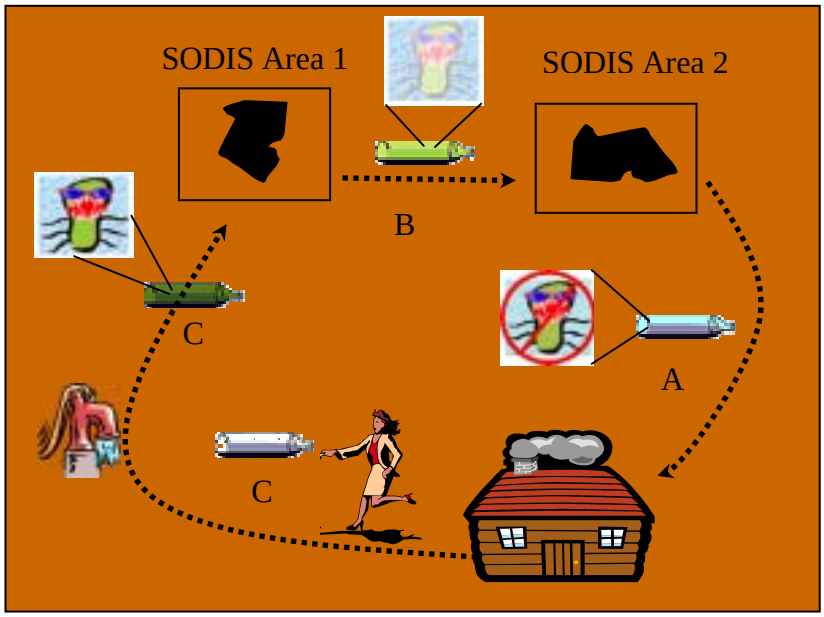
Morning of Day 2:

- Collect water with group B
- Place group B in SODIS Area 1
- Move group A from Area 1 to Area 2



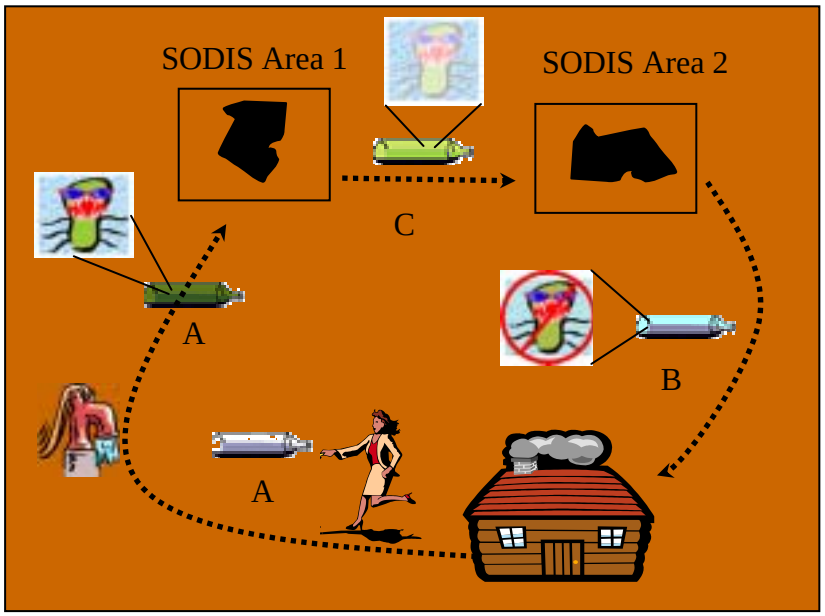
Morning of Day 3:

- Collect water with group C
- Place group C in SODIS Area 1
- Move group B from Area 1 to Area 2
- Bring group A home from Area 2 to drink



Morning of Day 4:

- Collect water with group A
- Place group A in SODIS Area 1
- Move group C from Area 1 to Area 2
- Bring group B home from Area 2 to drink



This now establishes an indefinite loop where a person goes out in the morning to fill up a group of bottles and returns the same morning with a group of bottles that have undergone two days of SODIS treatment. This has the added advantage that the bottles have been allowed to cool over night.

8.4 Anticipated Mistakes

Some bottles are placed in sunny areas in the morning but the areas become shady after a few hours.

Many people like to place their bottles on chairs, but the chair backs shade bottles after a few hours.

Some users expose the bottle with the black side on top.

Users don't plan well, become impatient, drink the water prematurely, and get sick.

Section VI: Summary and Conclusions

9 Summary and Conclusions

SODIS is a simple technology that operates on the principle that sunlight-induced DNA alteration, photo-oxidative destruction, and thermal effects will inactivate microorganisms. The treatment process consists of filling plastic bottles with water and exposing them to sunlight. Using this technique, 100% inactivation of total coliform, *E. coli*, and H_2S-producing bacteria was achieved after a 2-day exposure period under a variety of conditions. Based on these results in January, it is recommended that a "SODIS triangle" be applied to ensure every bottle receives 2 days of the SODIS process. Mathematical sunshine simulations suggest that SODIS would be applicable, on average, throughout Haiti year-round. However, this model does not take into account microclimates and mountainous areas may have limited success due to lower sunshine and temperature. This aspect needs further research. Overall, the results are encouraging and it is strongly recommended that SODIS be further investigated for at least some parts of Haiti. It is hoped that this extremely affordable point-of-use treatment technology can help alleviate the water quality problems that currently plague Haiti. To evaluate SODIS as a point-of-use treatment technology, it will be compared to the point-of-use water treatment criteria established in section 1.4 and summarized in Table 9-1.

Table 9-1. Point-of-Use Water Treatment Compliance Criteria (Lehr *et al.*, 1980; Shultz *et al.*, 1984)

Criteria	Compliance
Effective on many types and large numbers of pathogens	X[†]
Should perform regardless of water fluctuations	√
Must operate in appropriate pH and temperature range	√
Should not make the water toxic or unpalatable	√
Should be safe and easy to handle	√
Any chemical concentrations should be minor	√
Must provide residual protection against possible recontamination	X[‡]
Units must be affordable to all	√!
Should be adaptable to local conditions and variations	√
Specialized equipment should be produced locally	√
Must be accepted by local traditions, customs, and cultural standards	√
Must comply with national sanitation and pollution policies	√

[†] Although SODIS has been effective on large number of pathogens, there is still no data for many organisms

[‡] Indirectly provides some protection against recontamination because the disinfected bottle stays closed until consumption

EAWAG/SANDEC is currently studying the effects on other pathogens and the issue of providing residual protection is easily offset by the low cost of this technology. Every point-of-use treatment technology has it strong points and setbacks. SODIS would have the following advantages and disadvantages in Haiti.

Advantages:

- Inactivates or destroys pathogenic organisms
- Requires plastic bottles which are inexpensive, easy to handle, transport, and store
- Extremely low cost technology since its investment costs are low and its running costs are negligible
- Has simple application which is ideal for the household level
- Does not require chemical addition, which could be carcinogenic, have questionable availability, or change water taste and smell
- Makes use of locally available resources

Disadvantages:

- Does not improve the chemical water quality
- Requires favorable climate conditions: 5 hours of radiation above 500 W/m^2 and warm ambient temperatures, which may not be available in mountainous regions
- Should not be applied to raw water of turbidity higher than 30 NTUs
- Offers limited production capacity

Along with good point-of-use treatment methods, the population needs to be educated about water problems and potential solutions. Community health will not improve just because they have point-of-use technologies available to them; they must use them. SODIS would most likely only be applied if the target population were convinced it works. To stay healthy, and benefit from SODIS, users would need to become aware of the bacteriological routes of water borne diseases and how to avoid them. One of the biggest problems I witnessed is most people, especially children, don't know or care that their water contains pathogens. Even at locations with water purification systems, children were constantly drinking from contaminated sources. These types of action negate the effects of any water treatment technology.

Figure 9-1. Water in the Haitian Community

Ultimately, this point-of-use treatment option is very attractive as it could provide a safe source of water at the cost of a plastic bottle. It is hoped that this relatively new disinfection method will produce an economically feasible technology to improve water quality and public health in Haiti.

Appendix: Code Used for Sunlight Simulation

```
%  Numerical Model of Daily Sunlight Profile
%  Peter Oates
%  2/24/01
%  MIT

%clear;
clf;

% Data for total Energy obtained from NASA

% Set Trip = 1,2,3 for average, minimum, maximum, or 4 year
respectively
trip=1;

%  Set cal=1 if you want to run calibration plots for noon data
%  note: have to change the length of the n vector to average over the
appropriate time
cal=1;

%noon time calibration data
noondat1=[0.64 0.72 0.76 0.78 0.73 0.72 0.73 0.74 0.71 0.64 0.59
0.56]*1000;
noondat2=[0.62 0.70 0.75 0.76 0.71 0.69 0.70 0.72 0.68 0.61 0.56
0.56]*1000;
noondat3=[0.61 0.69 0.74 0.75 0.70 0.67 0.68 0.69 0.66 0.66 0.62
0.54]*1000;
noondat4=[0.68 0.75 0.80 0.80 0.76 0.74 0.74 0.75 0.72 0.66 0.62
0.61]*1000;
noondat5=[0.65 0.73 0.77 0.77 0.72 0.70 0.71 0.72 0.69 0.63 0.59
0.57]*1000;
noondat6=[0.63 0.70 0.75 0.75 0.69 0.66 0.67 0.69 0.66 0.60 0.56
0.56]*1000;

%My data for calibration
dat=[0.0000 120.0000 340.7500 519.0000 666.8333 793.6667 814.0000
749.6667 650.1667 461.3333 203.3333 65.33334 0.0000];

if trip==1
%Average Data Kw/m2/day
E=[4.68 5.32 5.99 6.30 6.16 5.99 5.96 5.86 5.61 4.95 4.50 4.28 %Area 1
   4.59 5.23 5.89 6.16 6.03 5.80 5.79 5.70 5.46 4.84 4.42 4.21 %Area 2
   4.51 5.16 5.86 6.13 5.98 5.69 5.68 5.58 5.36 4.76 4.36 4.13 %Area 3
   4.90 5.52 6.21 6.47 6.26 6.09 6.01 5.91 5.72 5.08 4.66 4.51 %Area 4
   4.79 5.38 6.03 6.22 6.04 5.80 5.75 5.68 5.49 4.91 4.54 4.40 %Area 5
   4.68 5.25 5.89 6.04 5.86 5.54 5.52 5.47 5.29 4.76 4.44 4.30 %Area 6
   4.55 5.15 5.82 5.99 5.79 5.40 5.37 5.31 5.15 4.66 4.36 4.21]; %Area
7
end

if trip==2
%Minimum Data
E=[4.40 5.05 5.67 5.62 5.39 5.55 5.78 5.45 5.00 4.38 3.99 3.91 %Area 1
   4.36 4.96 5.56 5.58 5.35 5.42 5.59 5.32 4.88 4.29 3.92 3.79 %Area 2
```

```
   4.34 4.87 5.52 5.54 5.31 5.36 5.48 5.23 4.91 4.13 3.90 3.70 %Area 3
   4.66 5.27 5.99 5.80 5.30 5.64 5.80 5.41 5.07 4.48 3.94 4.18 %Area 4
   4.57 5.14 5.80 5.73 5.21 5.39 5.58 5.23 4.80 4.36 3.88 4.01 %Area 5
   4.49 5.01 5.62 5.64 5.14 5.18 5.34 5.04 4.62 4.24 3.85 3.86 %Area 6
   4.41 4.90 5.55 5.60 5.14 5.07 5.23 4.91 4.63 4.08 3.87 3.74]; %Area
7
end

if trip==3
%Maximum Data
E=[4.99 5.58 6.22 6.56 6.82 6.35 6.24 6.10 5.89 5.28 4.82 4.50 %Area 1
   4.90 5.46 6.10 6.40 6.69 6.12 6.05 5.95 5.75 5.15 4.75 4.43 %Area 2
   4.79 5.40 6.10 6.47 6.61 6.01 5.98 5.86 5.75 5.13 4.73 4.36 %Area 3
   5.16 5.80 6.49 6.70 6.93 6.45 6.28 6.15 6.09 5.46 5.04 4.67 %Area 4
   5.07 5.62 6.33 6.50 6.75 6.11 5.98 5.92 5.81 5.23 4.90 4.58 %Area 5
   4.96 5.46 6.18 6.37 6.59 5.83 5.73 5.75 5.60 5.04 4.79 4.49 %Area 6
   4.82 5.39 6.07 6.41 6.49 5.78 5.62 5.69 5.58 5.05 4.74 4.42];  %Area
7
end
My_dat=[120 340.75 519 666.8333333 793.6666667 814 749.6666667
650.1666667 461.3333333 203.3333333 65.33333333];
T_dat=[7 8 9 10 11 12 13 14 15 16 17];

E=E*1000;   %Transforms kW=W
%E=5394; %my value
%T=[4:.1:20];
%T=[6:18]; %Increment by .5 for calibration
T=[6.25:.5:18.25]; %Increment by .5 for calibration
lsm=-.1533;
Tad=T+lsm;
Tm=[1:12];Tm=Tm'; %Time in months
base=zeros(1,length(T));
%T=[10];


IH=[];
FIHRAVE=[];
MASTER_AVE=[];
Seas=[];
%Latitude
Lat=[19.5 19.5 19.5 18.5 18.5 18.5 18.5]; % Latitudes Area 1-7
%Monthly Declination
dec=[-20.9 -13 -2.4 9.4 18.8 23.1 21.2 13.5 2.2 -9.6 -18.9 -23.0];

for j=1:7
   for i=1:length(dec)
      for k=1:length(T)
         hsa=acos(-
(tan(Lat(j)*pi/180))*tan(dec(i)*pi/180));hsa=hsa*180/pi; %sunset angle
%Matlab works in radians
         ha=(T(k)-12)*360/24;                                    %hour angle
         a=.409+.5016*(sin(hsa*pi/180-60*pi/180)); %coefficients
         b=.6609-.4767*(sin(hsa*pi/180-60*pi/180));   %coefficients
         A=(pi/24)*(a+b*cos(ha*pi/180));
         B=cos(ha*pi/180)-cos(hsa*pi/180);
         C=sin(hsa*pi/180)-(2*pi*hsa/360)*cos(hsa*pi/180);
         R=A*B/C; %t ratio
```

```
         Ih=R*E(j,i);   %intensity at the hour
         %Ih=R*E; %intensity at the hour

         IH=[IH
            Ih];  %vector that builds daily profile
      end
      %daylength=hsa/15*2
      Seas=[Seas IH];
      %fihrave=(IH(5,1)+IH(6,1)+IH(7,1)+IH(8,1)+IH(9,1))/5; %five hour
average correct

   %fihrave=(IH(10,1)+IH(11,1)+IH(12,1)+IH(13,1)+IH(14,1)+IH(15,1)+IH(1
7,1))/7; %three hour increment, must change T by .5

fihrave=(IH(10,1)+IH(11,1)+IH(12,1)+IH(13,1)+IH(14,1)+IH(15,1))/6;
%three hour increment, must change center weighted
      %fihrave=(IH(4,1)+IH(5,1)+IH(6,1)+IH(7,1)+IH(8,1)+IH(9,1))/6;
%three hour increment, must change center weighted



        IH=[];
      FIHRAVE=[FIHRAVE
         fihrave];
   end
   MASTER_AVE=[MASTER_AVE FIHRAVE];
   FIHRAVE=[];
end
supave1=mean(MASTER_AVE')

if cal==1
figure(1);
%plot(T,SI(:,1),T,SI(:,2),T,SI(:,3),T,SI(:,4),T,SI(:,5),T,SI(:,6),T,SI(
:,7),T,SI(:,8),T,SI(:,9),T,SI(:,10),T,SI(:,11),T,SI(:,12));
subplot(3,2,1);plot(Tm,MASTER_AVE(:,1),'-
',Tm,noondat1,'*','LineWidth',1.5,'MarkerSize',11);
axis([1 12 500 950]);
set(gca,'XTick',1:1:12)
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','June','July','Aug'
,'Sept','Oct','Nov','Dec'})
ylabel('W/m^2');
title('Area 1');

subplot(3,2,2);plot(Tm,MASTER_AVE(:,2),'-
',Tm,noondat2,'*','LineWidth',1.5,'MarkerSize',11);
axis([1 12 500 950]);
set(gca,'XTick',1:1:12)
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','June','July','Aug'
,'Sept','Oct','Nov','Dec'})
ylabel('W/m^2');
title('Area 2');

subplot(3,2,3);plot(Tm,MASTER_AVE(:,3),'-
',Tm,noondat3,'*','LineWidth',1.5,'MarkerSize',11);
axis([1 12 500 950]);
set(gca,'XTick',1:1:12)
```

```
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','June','July','Aug'
,'Sept','Oct','Nov','Dec'})
ylabel('W/m^2');
title('Area 3');

subplot(3,2,4);plot(Tm,MASTER_AVE(:,4),'-
',Tm,noondat4,'*','LineWidth',1.5,'MarkerSize',11);
axis([1 12 500 950]);
set(gca,'XTick',1:1:12)
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','June','July','Aug'
,'Sept','Oct','Nov','Dec'})
ylabel('W/m^2');
title('Area 4');

subplot(3,2,5);plot(Tm,MASTER_AVE(:,5),'-
',Tm,noondat5,'*','LineWidth',1.5,'MarkerSize',11);
axis([1 12 500 950]);
set(gca,'XTick',1:1:12)
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','June','July','Aug'
,'Sept','Oct','Nov','Dec'})
ylabel('W/m^2');
title('Area 5');

subplot(3,2,6);plot(Tm,MASTER_AVE(:,6),'-
',Tm,noondat6,'*','LineWidth',1.5,'MarkerSize',11);
axis([1 12 500 950]);
set(gca,'XTick',1:1:12)
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','June','July','Aug'
,'Sept','Oct','Nov','Dec'})
ylabel('W/m^2');
title('Area 6');
legend('Simulated','Observed')
end

Cloudy=[38.6 40.7 44.6 50.6 57.0 50.8 49.4 47.6 51.2 49.3 46.2 39.8  %
Area 1
        39.9 42.1 45.5 52.0 58.1 50.7 48.8 47.3 50.9 49.3 46.3 39.9  %
Area 2
        42.6 44.1 45.2 52.1 59.2 52.7 50.6 49.0 51.8 50.2 48.1 42.5  %
Area 3
        35.7 39.0 40.7 47.4 56.0 51.0 51.7 49.9 51.7 49.7 45.8 38.1  %
Area 4
        37.2 40.5 43.1 50.2 57.5 50.9 49.8 48.2 51.3 49.3 45.3 37.4  %
Area 5
        38.9 42.5 44.8 52.0 58.6 51.0 49.5 48.1 51.7 49.3 45.3 37.5  %
Area 6
        42.3 45.2 45.2 52.0 59.8 53.8 52.3 50.7 53.4 50.4 47.4 40.9];
% Area 7

     Rain=[3.03 3.03 3.18 3.32 3.71 3.82 3.84 4.05 4.20 4.25 3.85 3.32  % Area 1
           3.01 3.02 3.17 3.32 3.69 3.78 3.81 4.01 4.17 4.25 3.84 3.30  % Area 2
           3.00 3.02 3.17 3.32 3.67 3.76 3.78 3.95 4.12 4.23 3.85 3.27  % Area 3
           3.10 3.11 3.25 3.48 3.81 3.90 3.86 4.13 4.28 4.33 3.91 3.41  % Area 4
           3.09 3.09 3.24 3.48 3.81 3.85 3.84 4.09 4.25 4.33 3.89 3.40  % Area 5
           3.07 3.08 3.24 3.48 3.80 3.82 3.83 4.07 4.21 4.32 3.88 3.39  % Area 6
           3.06 3.09 3.24 3.47 3.80 3.81 3.80 4.00 4.13 4.29 3.88
3.35];   % Area 7
```

```
     Heat=[25.5 25.2 25.4 26.0 26.5 27.5 27.7 27.8 27.8 27.6 27.0 26.0  % Area 1
           25.1 24.9 25.2 25.8 26.3 27.2 27.4 27.5 27.5 27.3 26.6 25.7  % Area 2
           25.2 24.9 25.1 25.7 26.3 27.2 27.4 27.6 27.6 27.4 26.7 25.8  % Area 3
           25.9 25.6 25.9 26.5 26.9 27.7 27.9 28.0 27.9 27.7 27.2 26.4  % Area 4
           25.2 25.1 25.5 26.2 26.5 27.2 27.3 27.4 27.2 27.1 26.5 25.6  % Area 5
           24.5 24.5 25.1 25.9 26.1 26.7 26.7 26.8 26.5 26.5 25.8 24.9
%Area 6
           24.9 24.7 25.1 25.8 26.2 26.9 27.0 27.1 27.0 26.9 26.3
25.4];   % Area 7

          MASTER_AVE=Cloudy';

Thresh=500*ones(1,length(Tm));Thresh=Thresh'; %disinfection threshold
figure(2)
%plot(T,Seas)
%plot(Tm,Thresh,'k:',Tm,MASTER_AVE(:,1),'y-
x',Tm,MASTER_AVE(:,2),':m',Tm,MASTER_AVE(:,3),'-
.+c',Tm,MASTER_AVE(:,4),'-*r',Tm,MASTER_AVE(:,5),'--
g',Tm,MASTER_AVE(:,6),'b-.',Tm,MASTER_AVE(:,7),'k-
','LineWidth',2,'MarkerSize',8);
plot(Tm,MASTER_AVE(:,1),'y-
x',Tm,MASTER_AVE(:,2),':m',Tm,MASTER_AVE(:,3),'-
.+c',Tm,MASTER_AVE(:,4),'-*r',Tm,MASTER_AVE(:,5),'--
g',Tm,MASTER_AVE(:,6),'b-.',Tm,MASTER_AVE(:,7),'k-
','LineWidth',2,'MarkerSize',8);
%plot(Tad,IH,'-',T_dat,My_dat,'o','Markersize',8,'lineWidth',2)
%plot(T,IH,T,base);
%plot(T,IH,'-')
set(gca,'XTick',1:1:12)
set(gca,'XTickLabel',{'Jan','Feb','Mar','Apr','May','June','July','Aug'
,'Sept','Oct','Nov','Dec'})
%set(gca,'XTick',5:1:19)
%xlabel('Hours from Midnight')
ylabel('Percent Daytime Cloud Cover');
title('Average Percent Daytime Cloud Cover');
%title('Average Temperature Profile')
%ylabel('Temperature [C]');
%ylabel('W/m^2');
%axis([1 12 24 28.5]);
axis([1 12 35 65]);
%title('Simulated Average 5-hr Intensity Average Derived from Monthly
Energy for all areas of Haiti');
%title('Simulated Average 5-hr Intensity Average Derived from Monthly
Energy');
%legend('Jan','Feb','Mar','Apr','May','June','July','Aug','Sept','Oct',
'Nov','Dec');
%legend('Threshold','Area 1','Area 2','Area 3','Area 4','Area 5','Area
6','Area 7');
legend('Area 1','Area 2','Area 3','Area 4','Area 5','Area 6','Area 7');
%axis([1 12 450 850]);
```

References

1. Country Profile: Haiti. 2000. ABCNews: http://www.abcnews.go.com/reference/countries/Haiti.html. (cited 6 Feb. 2001).

2. Acra, A., Jurdi, M., Mu'allem, H., Darahagopian, Y. & Raffoul, Z. (1990). Water Disinfection by Solar Radiation: Assessment and Applications. International Development Research Center. Ontario, Canada.

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

4. Bertilsson, S., Stepanauskas, R., Cuadros-Hanson, R., Granéli, W., Wikner, J., & Tranvik, L. (1999). Photochemically induced changes in bioavailable carbon and nitrogen pools in a boreal watershed. Aquatic Microbial Ecology, 19, 47-56.

5. Bethel Missions of Haiti Vision 2000 New Medical Clinic. (2000). [Video-tape].

6. Brenner, D. J. (1984). Facultatively anaerobic gram-negative rods, In N. R. Krieg and J. G. Holt (Eds.) Bergey's Manual of Systematic Bacteriology, 9th edn. Baltimore, MD. Williams and Wilkins.

7. Brock, T., Madigan, T., Martinko, J., & Parker, J. (2000). Biology of Microorganisms. Prentice Hall.

8. Brock, T. (1981). Calculating solar radiation for ecological studies. Ecological Modeling, 14, 1-19.

9. Brooks, F. A., Miller, W. (1963). Availability of solar energy. In A. M. Zarem and D. Erway (Eds.) Introduction to the utilization of solar energy. (pp. 30-58). New York: McGraw-Hill.

10. Bukhari, Z., Hargy, T. M., Bolton, J. R., Dussert, B., & Clancy, J. L. (1999). Medium-pressure UV for oocyst inactivation. J Am. Wat. Wks. Assn. 91(3), 86-94.

11. Bushaw, K. L., Zepp, R. G., Tarr, M. A., Schulz-Jander, D., Bourbonniere, R. A., Hodson, R. E., Miller, W. L., Bronk, D. A., & Moran, M. A. (1996). Photochemical release of biologically available nitrogen from aquatic dissolved organic matter. Nature, 381, 404-407.

12. Chlorine Chemistry Council. Drinking Water Chlorination White Paper. http://www.cr3.org/newsroom/whitepapers/whitepapercl.htm. (cited 5 May. 2000).

13. Clancy, J. L., Bolton J. R., & Dussert, B. (1998). Inactivation of Cryptosporidium parvum oocysts using medium-pressure ultraviolet light in bench and pilot scale studies. In American Water Works Association Water Quality and Technology Conference. American Water Works Association, San Diego, CA.

14. Cooper, P. I. (1969). The absorption of solar radiation in solar stills. Sol. Energy, 12, 3.

15. CONADEPA. (1984). Bulletin de Statistiques et d'Epidemiologie, Departement de la Sante Publique et de la Population.

16. Craik, S. A., Gordon, R. F., Bolton, J. R., & Belosevic, M. (2000). Inactivation of Giardia Muris Cysts using Medium-Pressure Ultraviolet Radiation in Filtered Drinking Water. Wat Res. Vol.. 34, No. 18. 4325-4332.

17. Cubbage, C. P., Gannon, J. J., Cochran, K. W., Williams, & G. W. (1979.) Loss of Poliovirus 1 in river water under simulated field conditions. Wat. Res. 13, 1091-1099.

18. DATPE. (1984). Regions et Strategies de Developpment Regional, Ministere du Plan, Port-au-Prince.

19. Duffie, J. A. & Beckman, W. A. (1980). Solar Engineering of Thermal Processes. New York: Wiley-Interscience.

20. EAWAG/SANDEC. (1999, March). SODIS Conference Synthesis. http://www.sodis.ch/synthesis_e.html (cited 5 Nov. 2000).

21. EAWAG/SANDEC. (1997, August). SODIS News No. 1.

22. EAWAG/SANDEC. (1999, May). SODIS News No. 4. http://www.sodis.ch (cited 5 Nov. 2000).

23. EAWAG/SANDEC. (1998, August). SODIS News No. 3. http://www.sodis.ch (cited 5 Nov. 2000).

24. EAWAG/SANDEC. Technical Notes. http://www.sodis.ch (cited 5 Nov. 2000).

25. Environmental Concern (EC) Khon Kaen. (1997). SODIS Demonstration Projects. Final Evaluation. Khon Kaen, Thailand.

26. Farmer, J. J., Davis, B. R., Hickman-Brenner, F. W., McWorter, A., Huntley-Carter, G. P., Asbury, M. A., Riddle, C., Wathen-Grady, H. G., Elias, C., Fanning, G. R., Steigerwalt, A. G., O'Hara, C. M., Morris, G. K., Smith, P. B., & Brenner, D. J. (1985). Biochemical Identification of new species and biogroups of *Enterobacteriaceae* isolated from clinical specimens. J. Clin. Microbiol., 21, 46-76.

27. Fass, S. (1982). Water and Politics: The Process of Meeting a basic need in Haiti. Development and Change. London: Sage Publ.

28. Feachem R., Bradley, D., Garelick, M., & Mara, D. (1983). Sanitation and Disease, Health Aspects of Excreta and Wastewater Management. UK: John Wiley and Sons.

29. Feng, P. C. S., & Hartman, P. A. (1982). Fluorogenic assay for immediate confirmation of *Esherichia coli*. Appl. Environ. Microbiol., 50, 1383-1387.

30. Ford, T. E., & Colwell, R. R. (1996). A Global Decline in Microbiological Safety of Water: A Call for Action. American Academy of Microbiology. Standard Methods for the Examination of Water and Wastewater, ed. 20. American Public Health Association. Washington D.C.

31. Fujioka, R., Tenno, R., & Kansako, S. (1988). Naturally occurring fecal coliform and fecal streptococci in Hawaii's freshwater systems. Toxic Assess., 3, 613-630.

32. Grant, M. A., & Ziel, C. A. (1996). Evaluation of a simple screening test for fecal pollution in water. J. Water SRT., 45(1), 13-18.

33. Gao, H., & Zepp, R. G. (1998). Factors influencing photoreactions of dissolved organic matter in a coastal river of the Southeastern United States. Environ. Sci. Technol., 32, 2940-2946.

34. Gibbons, J., & Laha, S. (1997). Water purifications systems: a comparative analysis based on the occurrence of disinfection by-products. Environmental Pollution, 106, 425-428.

35. Halliwell, B., & Gutteridge, M. C. (1999). Free Radicals in Biology and Medicine. Oxford: Oxford Univ. Press.

36. HARZA. (1979). Water Resources Study for Haiti. Final Report. HARZA Engineering Co. Chicago.

37. Kapuscinski, R. B., & Mitchell, R. (1982). Sunlight-Induced mortality of viruses and *Escherichia coli* in coastal seawater. Env. Sci. Technol., 17, 1-6.

38. Kasper, P., Guillen, I., Rivelli, D., Meza, T., Velazquez, H., Mino, D., Pozolli, L., Nunez, C., & Zoulek, G. (1992). Evaluation of a simple field test for the detection the quality of drinking water systems. Trop Med Parasitol., 43, 124-127.

39. Khayyat, A. M. (2000). Study of Point of Use Treatment Methods for the Disinfection of Drinking Water in Nepal. Massachusetts Institute of Technology Masters Thesis. Cambridge, MA.

40. Kieber, D.J., McDaniel, J., & Mopper, K. (1989). Photochemical source of biological substrates in seawater: Implications for carbon cycling. Nature, 341, 637-639.

41. Kromoredjo, P., & Fujoka, R. S. (1991). Evaluating three simple methods to assess the microbial quality of drinking water in Indonesia. Environ. Toxicol. Water Quality, 6, 259-270.

42. Lantagne, D. (2001). Trihalomethane Production in Household Water Filtration Systems in Rural Haiti. Massachusetts Institute of Technology Masters Thesis. Cambridge, MA.

43. Lawand T. A., Alward R., Odeyemi, O., Habn J., Kandpal, T. C., & Ayoub, J. (1988). Solar Water Disinfection. *Proceedings of a work-shop held at the Brace Research Institute. Montreal, Canada.* International Development Research Center, IDRC-MR231e, Ontario, Canada.

44. Lehr, J. H., Gass, T. E., Pettyjohn, W., A., & DeMarre J. (1980). Domestic Water Treatment. New York: McGraw-Hill.

45. Library of Congress. (1979). Draft environmental report on Haiti. Science and Technology Division. Washington, D.C.

46. Lindell, M. J., Granéli, W., & Tranvik, L. J. (1995). Enhanced bacterial growth in response to photochemical transformation of dissolved organic matter. Limnol. Oceanogr., 40(1), 195-199.

47. Maier, R. M., Pepper, I. L., & Gerba, C. P. (2000). Environmental Microbiology. Canada: Academic Press.

48. Manja K. S., Maurya, M. S., & Rao, K. M. (1982). A simple field test for the detection of fecal pollution in drinking water. Bull. World Health Org., 60, 797-801.

49. Martins, M. T., El-Shaarawi, A. Dutka, B. J., Pellizari, V. H., Alfredo, G., Ribeiro, G., & Matsumoto, E. F. (1989). Coliphage association with coliform indicators: a case study – Brazil. Toxicity Assessment., 4, 329-338.

50. Masters, G. M. (1997). Introduction to Environmental Engineering and Science. 2nd edition. Upper Saddle River: Prentice Hall.

51. Mathews, C. K., & Van Holde, K. E. (1996). Biochemistry Second Edition. The Benjamin/Cummings Publishing Company Inc.

52. McGuigan, K. G., Joyce, T. M., Conroy, R. M., Gillespie, J. B., & Elmore-Meegan, M. (1998). Solar Disinfection of drinking water contained in plastic bottles:

characterizing the bacterial inactivation process. J. Appl. Microbiol., 84(6), 1138-48.

53. McVeigh, J. C. (1977). Sun Power – an introduction to solar energy. New York: Pergamon Press.

54. Mechsner, K. L., & Fleischmann, T. (1990). Ultraviolettdesinfektion des Wasssers und bakterielle Wiederverkeimung. Gas-Wasser-Abwasser., 70(6), 417-421.

55. Mechsner, K. L., Fleischmann, T., Mason C. A., & Hamer G. (1991). UV Disinfection: Short term inactivation and revival. Wat. Sci. Tech. 24(2), 339-342.

56. Mechsner, K. L., Fleischmann, T. (1992). Vergleichende Untersuchungen zur Wiederverkeimung des Wassers nach Ultrviolettdesinfektion. Gas-Wasser-Abwasser., 72, 807-811.

57. Metcalf & Eddy. (1991). Revised by Tchobanoglous, George; Franklin L. Burton. Wastewater Engineering: Treatment, Disposal and Reuse. Boston: Irwin McGraw-Hill.

58. Michaels, T. (1979). Solar energy utilization. New York: Van Nostrand Reinhold.

59. Milankovitch, M., (1930). Mathematishce Klimalehre und Astonomische Theorie der Klimaschwankungen. Handbuch der Klimatologie, Band I, Teil A. Gebruder Borntraeger, Berlin.

60. Miller, W. L. (1998). Effects of UV radiation on aquatic humus: Photochemical principles and experimental considerations. In D. O. Hessen and L. J. Tranvik (Eds.) Aquatic Humic Substances – Ecology and Biogeochemistry. (pp. 125-143).

61. Moberg, L. J. (1985). Flurogenic assay for rapid detection of *Esherichia coli* in food. Appl. Environ. Microbiol., 50, 1383-1387.

62. Mopper, K., & Stahovec, W. L. (1986). Sources and sinks of low molecular weight organic carbonyl compounds in seawater. Mar. Chem., 19, 305-321.

63. Moran, M. A. & Zepp, R. G. (1997). Role of photoreactions in the formation of biologically labile compounds from dissolved organic matter. Limnol. Oceanogr., 42, 1307-1316.

64. Morris, R. D., *et al*. (1996). Am. J. Public Health., 86(2), 237-239.

65. NASA Langley Research Center Atmospheric Sciences Data Center. (2001). Surface Meteorology and Solar Energy Data Set. http://eosweb.larc.nasa.gov/sse/ (cited 6 Feb. 2001).

66. National Research Council. (1996). Use of Reclaimed Water and Sludge in Food Crop Production. Washington D.C.: National Academy Press.

67. New Scientist Magazine. (2000). Safe to Drink. vol. 167 issue 2253.

68. NOAA. (2001). http://www.noaa.gov (cited 6 Feb. 2001).

69. OAS. (1972). Mission d'Assistance Technique Integree. Rapport Final. Haiti.

70. PAHO (Pan American Health Organization). (1999). Haiti: Basic Country Health Profiles, Summaries 1999. http://www.paho.org/english/sha/prflhai.htm (cited 9 Feb. 2001).

71. Per Magnus, J. J. K. J., Skrondal, A., Alexander, J., Becher, G., Krogh, & T., Dybing, E. (1999). Water Chlorination and Birth Defects. Epidemiology., 5, 513-517.

72. Raab, O. (1900). Ueber die wikung fluorescierender stoffe auf infusorien. Zeitschrigt fuer Biologie, 39, 524-546.

73. Raven P. H., Johnson G. B. (1999). Biology Fifth Edition. McGraw-Hill

74. Reed, R. H. (1997). Solar inactivation of fecal bacteria in water: The critical role of Oxygen. Lett. Appl. Microbiol., 24, 276-280.

75. Reed, R. H. (1997). Sunshine and Fresh Air: A practical approach to combating water-borne disease. Waterlines. 15 (4), 295-296.

76. Reed, R. H. (1996). Sol-Air Water Treatment. 22nd WEDC Conference: Discussion paper. New Delhi, India. 295-296.

77. Roberts, N. C., Freeman, B. O., & Bradford, H. B. (1980). A unique environmental occurrence of hydrogen sulfide positive *Escherichia coli.* Canad. J. Microbiol., 26, 232-234.

78. Sabins, F. F. (1978). Remote Sensing: principles and interpretation. San Francisco: W. H. Freeman.

79. Shah, S. K., McBean, E. A., & Anderson, W. A. (1996). Preliminary Studies into the disinfection of potable water using solar radiation. Canadian Journal for Civil Engineering, 23, 373-380.

80. Sheladia Associates. (1983). Integrated Agricultural Development Project Dubreuil. Report prepared for USAID/Haiti.

81. Shultz, C. R., & Okun, D. A. (1984). Surface Water Treatment for Communities in Developing Countries. New York: John Wiley and Sons.

82. Solomon, T. W. G. (1996). Organic Chemistry. New York: John Wiley and Sons.

83. Sommer, B., Marino, A., Solarte, Y., Salas, L. M., Dierolf, C., Valiente, C., Mora, D., Rechsteiner, R., Setters, P., Wirojanagud, W., Ajarmeh, H., Al-Hassan, A., & Wegelin, M. (1997). SODIS – an Emerging Water Treatment Process. J. Water SRT-Aqua. 46(3), 127-137.

84. Stumm W., & Morgan, J. J. (1995). Aquatic Chemistry. Chemical Equilibria and Rates in Natural Waters. 3rd ed. New York: John Wiley and Sons.

85. Trussell, R. R. (1999). An overview of disinfectant residuals in drinking water distribution dystems. Journal of Water Services Research and Technology-Aqua., 48(1), 2-10.

86. USAID. (1985). Haiti, Country Environmental Profile: A Field Study

87. van Zyl, N. (2001). Sodium Hypochlorite Generation for Household Water Disinfection in Haiti. Massachusetts Institute of Technology Masters Thesis. Cambridge, MA.

88. Wegelin, M., Canonica, S., Mechsner, K., Pesaro, F. & Metzler, A. (1994). Solar Water Disinfection: Scope of the process and analysis of radiation experiments. J. Water SRT-Aqua. 43(3), 154-169.

89. WHO (World Health Organization). (1979). Environmental health criteria 14: Ultraviolet radiation. Geneva: WHO.

90. WHO. (1996). Geneva.

91. Wunderlich, W. (1972). Tennessee Valley Authority Division of Water Control Planning Engineering Laboratory. Heat and Mass Transfer between a Water Surface and the Atmosphere. Water Resources Research: Laboratory Report No. 14. Norris, Tennessee.

92. Yayasan, D. D. (1997). Solar Disinfection System – Field Study. Final Report.

93. Yun, E. J. & Y. N. Lee. (2000). Production of two different catalase-peroxidases by *Deinococcus radiophilus*. FEMS Microbiol. Letters, 184, 155-159.