International Journal of Water Resources and Arid Environments 6(2): 205-215, 2017
ISSN 2079-7079

Exposure Period Assessment for Solar Disinfection (Sodis) under Uncertain Environmental Conditions: A Fuzzy Rule-Based Model

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Abstract: Solar disinfection (SODIS) is a sustainable disinfection technology for developing countries with sufficient sunshine hours. For complete inactivation of pathogens, the required exposure period depends on certain process parameters, including number of pathogens, water turbidity and cloud cover conditions. SODIS can be effectively used for turbidity up to 30 Nephelometric Turbidity Unit (NTU) under changing cloud cover conditions, i.e., full sunny to overcast. Past studies mostly have explored extreme boundary conditions to evaluate the effectiveness of the process and not the intermediate conditions (e.g., 10 or 20 NTU turbidity and 40 to 60% cloud cover conditions). Moreover, there are different possible uncertainties due to measurement errors, limited data and vagueness in human judgment for assessment of suitable exposure duration while changing process parameters. To deal with inherent uncertainties, a fuzzy rule-based model is developed to estimate the required exposure period for achieving complete removal of fecal coliforms under varying turbidity (i.e., any turbidity level between 0 NTU and 30 NTU) and cloud cover conditions (i.e., full, partially cloudy and overcast). The model has also been validated with the data obtained from randomized SODIS experiments over a period of 3 years to accommodate seasonal and weather variations. A close agreement between the model results and measured values was found with high *R-squared* value of greater than 0.9. Surface viewers developed in this study using fuzzy logic toolbox in MATLAB can be effectively used to determine the exposure period for complete removal of fecal coliforms withvarying level of source water pollution (i.e., 2, 3 and 4 log reductions).

Key words: Solar Disinfection · SODIS · Water Treatment · Drinking Water · Uncertainty · Fuzzy Rule-based Modeling

INTRODUCTION

Access to safe drinking water is a right of every human being. As per the Human Development Report (HDR) for the 2015, more than 660 million people around the world are still using unimproved sources of drinking water [1] due to lack of technical and financial resources. The fecal contamination of drinking water may cause diarrhoea, typhoid, viral and bacterial gastroenteritis and hepatitis-A [2]. Millions of people living in urban slum dwellers have lack of adequate sanitation facilities; they also face the scarcity of safe drinking water which increases the risk of communicable diseases, particularly among children [3]. According to the United Nations Children's Fund (UNICEF) estimates, around 1,800 children under the five years of age die every day from diarrhoeal diseases [4]. The situation in developing countries is certainly alarming, for instance out of 783 million people living without improved drinking water in the world, there are 119 million in China, 97 million in India and 15 million in Pakistan, remaining are living in Indonesia, Bangladesh, Nigeria, Kenya and Sudan [4, 5]. Efficient treatment systems such as conventional filtration and expansive disinfection (e.g., ozonation and ultra-violet radiations) technologies might be economically viable for urban slums and rural areas in developing countries. Thus, research should be continued for developing new technologies and to improve of effectiveness of existing sustainable and inexpensive disinfection methods.

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Solar water disinfection (SODIS) has been widely recognized in the past two decades as the most cost effective and easy to use method at household level, particularly for developing countries [6]. Solar radiations above 500 W/m^2 are required with at least 3-5 sunshine hours (SSH) for effective disinfection [7]. It is interesting to know that all of the above stated countries are located in the most suitable region for SODIS application. Studies of SODIS application have reported immense reduction in risk of water borne diseases in various developing countries of Africa, Asia and Latin America [8, 9, 10].

In the low cost conventional SODIS process, 0.5 to 2 liter polyethylene terephthalate (PET) transparent bottles are filled with contaminated water and exposed to sunlight. One full sunshine hour (SSH) is considered when there is 0% cloud cover throughout this period. UV-A radiations (in the range of 320-400nm) directly kill the disease causing microorganisms; while, the infrared radiations imped the protein function to inactivate the pathogens by increasing the water temperature in the bottle [11]. During solar exposure, the cloud cover can vary form full sunny (0% cover) to overcast (100% cover). The bottle with low turbidity water should be exposed to direct sunlight for at least 6 hours (including noon hours) on primarily sunny days, or for two consecutive days when the sky is more than 50% covered [12]. SODIS process is enhanced at ambient temperatures higher than 20°C; however, thermal inactivation occurswhen the water temperatures is higher than 40°C [10].

The SODIS process depends on SSH, water turbidity, atmospheric temperature and number of FCs [13]. United States Environmental Protection Agency (USEPA) defines both the turbidity and fecal coliforms (FCs) as pollution indicators. There are other measures of water pollution, but this research focuses on these two [14]. A strong inter-relation also exists when the FCs harbour themselves behind the suspended particles (present in higher turbidities) for not exposing themselves to UV-radiations. Turbidity in drinking water should preferably be less than 1 NTU; however, when there sources are limited, up to 5 NTU is acceptable for small or rural water supplies [15]. Nevertheless, higher values of both the turbidity and FCs are common in developing countries, particularly for surface water sources [16, 17, 18, 19]. It is desirable that fecal coliforms are undetectable in 100 mL sample to avoid any possibility of health risk. Though the SODIS process can be applied to the water with turbidity up to or less than 30 NTU [7]; studies have also been conducted for higher turbidities [17, 18].

Several studies evaluated the effects of agitation, oxygen, container volume, possibility of regrowth, addition of chemicals, types of reactors and reflective and non-reflective materials in the past [20 - 26]. Detailed literature review of all these studies is out of scope of this paper; a summary of some of the studies conducted in developing countries in the past is presented in Table 1 (modified after [13]). Capital cost and operational difficulties are the main issues in using chemicals and reactors at the household level.Studies also found no potential associated health risks with the use of PET bottles [23, 27 – 29]. High turbidity levels (>30 NTU) are common in developing countries, but such high turbidities might not be free from health risk. WHO (2002) recommended to pass the raw water through a clean fine cloth to reduce higher turbidities to achieve desirable results from SODIS process [30]. SODIS is a sustainable low cost disinfection method for rural areas in developing countries; use of half black bottle, chemicals, reflectors and adding oxygen are not practically feasible in all conditions.

Exposure period certainly increases for higher turbidity and cloud cover conditions. Most of the studies in Table 1 evaluated turbidities less than 5 NTU or higher than 30 NTU. Secondly, SODIS was mostly applied to extreme cloud cover conditions, i.e., either full sunny or overcast. For the first time, Haider *et al.* (2014) developed a first order kinetics model for estimating SODIS exposure period under varying turbidity between 0 NTU and 30 NTU and cloud cover conditions (full sunny to overcast) [13]. They also developed the characteristics curves for end user and found that required exposure period significantly varies with changing turbidity, cloud cover as well as number of FCs. For instance, raw water with higher turbidities (20 NTU and 30 NTU) should be exposed to SODIS for more than one day with 8 to 14 hours sun exposure to achieve 3 to 4 log-reductions. While, for 0 to 5NT, only 2 to 4 hours exposure is required to achieve complete inactivation of FCs. Their model can also predict the exposure period for partial cloudy conditions and lower turbidities (up to 10 NTU).

All the above mentioned studies have not considered the effect of different types of uncertainties exist in estimation of model parameters. The uncertainties could be due to: i) measurement errors in turbidity and FCs estimation, ii) limited number of experiments not covering entire range of environmental and weather conditions and iii) use of climatic data available from local or regional climatological stations, which shows average hourly

Table 1: Summary of literature review, modified after [13]

Name of the Investigator and Location	Study Duration	No of samples analysed	Turbidity range	Cloud conditions	Type of Bacteria	Chemicals used	Comments
Haider *et al*. (2014) [13] Pakistan	3 years	40	0 to 30NTU	Full sunny to overcast (varying conditions)	- *Fecal coliforms*	None	•Turbidity range was considered •Cloud cover variations considered
Marques *et al.* (2013) [31] Southeastern Brazil defined	1 year	12	5 to 60	-	- *Salmonella sp.* - *Escherichia coli*	None	•black-backed PET bottles •asbestos roofing. And aluminium foil comparison • range of cloud cover conditions not clearly as % or *OKTAS*
Hindiyeh and Ali (2010) [22] Jordan	6 months	3	0.6 -2.6NTU	Sunny	- *Total coliforms* - *Fecal coliforms*	None	•Insufficient* number of experiments •Low turbidity levels were considered •Cloud cover variations were not considered
Fisher *et al* (2008) [25] Haiti & India	2 days	2	0 - 5NTU	Sunny	- *Escherichia coli*	-Hydrogenperoxide - lime juice - copper metal	•Insufficient* number of samples •Use of chemicals may not be feasible at household level •Less than 5NTU turbidity considered •Cloud cover variations were not considered
Boyle *et al* (2008) [32] Bolivia & Spain	2 days	2	-	- full sunny - overcast	- *Campylobacter jejuni* - Yersinia enterocolitica - S. epidermidis - Escherichia coli	None	•Insufficient* number of samples •Partial cloud conditions were not studied • Mainly SODIS application on different species was studied •Different turbidity levels were not considered
Mahvi (2007) [33] Iran	Fall season	3	1 NTU	Clear sky	-*Fecal coliforms*	None	•Insufficient* number of samples •Clear water samples with less than 1NTU turbidity were considered •Cloud cover variations were not considered
Rodrigues *et al* (2007) [24] Brazil	-	12	3 NTU &15 NTU	Clear sky	- *Escherichia coli*	TiO_2	•Use of chemicals may not be feasible at household level • Cloud cover variations were not considered
Oates *et al* (2003) [11] Haiti	9 days	7	0.7 – 1.9 NTU	- Sunny - overcast	- *Total coliforms* - *Escherichia coli*	None	•Only very low turbidity levels were considered •Partial cloud conditions were not studied
Kehoe *et al* (2001) [17] Malaysia & Ireland	4 days	6	0, 30, 100 and 300 NTU	- clear - overcast	- *Escherichia coli*	None	•Insufficient* number of samples •Variation between 0 and 30NTU were not considered •Partial cloud conditions were not studied
Reed (1997) [21] Newcastle UK	2 months	4	-	Sunny	- *Escherichia coli* - *Ent. faecalis*	None	•Insufficient* number of samples • Turbidity was not considered • Cloud cover variations were not considered

* Insufficient for modeling

variations for ambient temperature and cloud cover conditions. Therefore, the main objective of this study is to develop a model for estimating exposure time for SODIS application under different turbidity and cloud cover conditions as well as addressing the above stated uncertainties. The fuzzy rule-based modeling will be used to deal with the uncertainties and for establishing linguistic ranges for different factors to facilitate common end users. As the purpose of this study is sustainable SODIS application in developing countries, simple 1.5 L PET bottles were used without chemicals, paints and/ or reflective surfaces.

MATERIAL AND METHODS

The modeling framework developed in this study is shown in Figure 1. As a first step, geographical and climatological data was collected to estimate daily and hourly solar radiation. Randomized SODIS experiments were conducted at different turbidity levels and cloud cover conditions. Analysis of variance (ANOVA) was used to identify the significance of various process parameters and their interactions. A fuzzy rule based modeling was used to deal with the uncertainties associate with data limitations and measurements errors. The model results are compared with the measured data. Finally, a surface viewer was developed using fuzzy logic toolbox in MATLAB to assess the required exposure period for pragmatic application of the developed model at household level.

Study Area and Data Collection: Experiments were performed at the Institute of Environmental Engineering and Research (IEER), University of Engineering and Technology (UET), Lahore, Pakistan. Thelocation of the study area is 31°34’39”N; 74°21’25”E and approximately is 714ft (218m) higher than the mean sea level. The highest temperatures in Lahore varies from 40°C to 48°C during May, June and July, followed by the monsoon periods with the average rainfalls occurs up to 500mm per annum. The coolest months are December and January with the temperature variations between 5°C and 20°C. The area seems to be highly suitable for SODIS process with the sunshine hours of 8.5 (i.e., average daily) and 3094 (i.e., average annual) [34].

For SODIS experiments, ground water was drawn from the tap installed at the IEER laboratory. Municipal wastewater was collected from a septic tank in UET Lahore for seeding (to add FCs) the water samples. For estimating the number of FCs, the Most Probable Number (MPN) test was carried out as per the Standard Methods for the Examination of Water and Wastewater [35].

The local soil was passed through a sieve (No. 200) to generate artificial turbidity in the SODIS bottles. The sieved particles were stirred for 30 minutes in a jar and allowed to settle for next 24 hours. The supernatant water with 30 NTU to 50 NTU turbidity was used as a stock

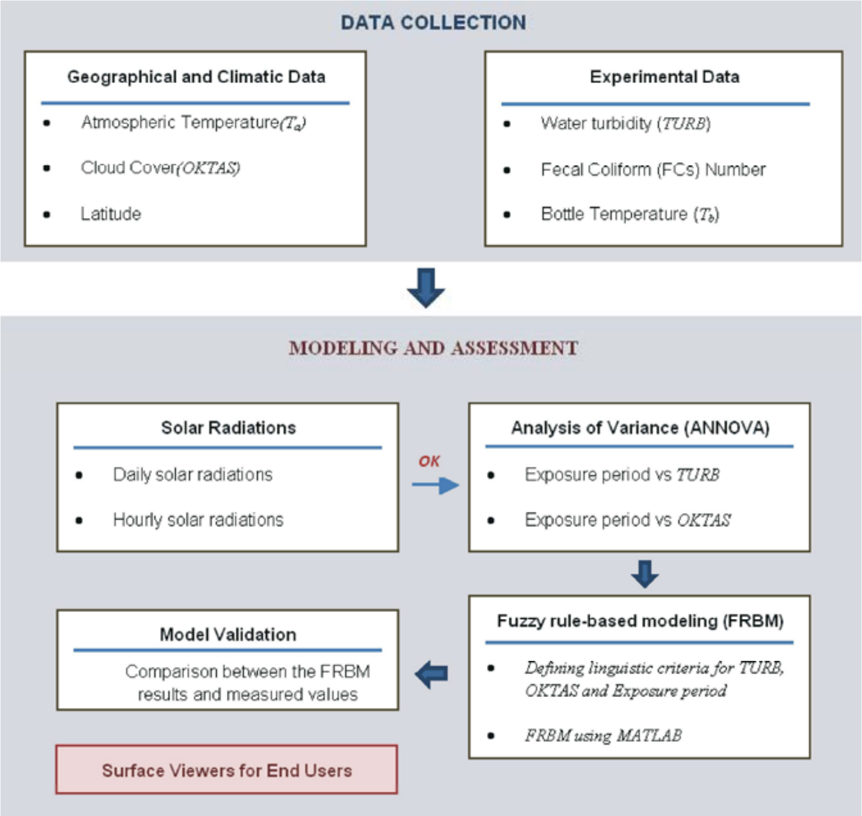

Fig. 1: Proposed framework for modeling exposure period under uncertainties for SODIS application in developing countries modified after (Haider *et al.* 2014) [13]

Table 2: Climatic data with sampling dates, sample turbidity and initial value of fecal coliforms (Source: Haider *et al.* 2014)

Sample No.	Date of sampling	Julian Day (n_j)	Mean Daily Temperature (°C)	Sunshine hours "*n*" (hr)	Day length "*N*" (hr)	Sample Turbidity (NTU)*	Initial F-Coli (MPN/100ml)
1	Jan-28-2008	28	16	6.3	10.6	30	70
2	Feb-04-2008	35	14	5.3	10.8	30	920
3	Feb-12-2008	43	18	11.0	11.0	30	70
4	Feb-13-2006	44	24	2.0	11.0	10	1600
5	Apr-26-2006	116	40	11.6	13.3	10	17
6	May-05-2008	126	36	8.3	13.5	30	920
7	May-10-2006	130	39	13.0	13.7	10	110
8	May-20-2008	141	35	5.7	13.9	30	920
9	May-29-2007	149	36	10.6	14.0	20	79
10	May-31-2006	151	39	9.6	14.1	20	79
11	Jun-05-2007	156	40	12.6	14.1	20	70
12	Jun-07-2006	158	38	6.8	14.1	20	44
13	Jun-19-2007	170	32	10.1	14.2	20	140
14	Aug-07-2007	220	35	7.5	13.5	20	110
15	Sep-11-2007	254	30	8.1	12.5	30	1600
16	Sep-20-2005	263	33	11.1	12.2	5	17
17	Sep-27-2005	270	33	10.4	12.0	5	8
18	Oct-04-2005	277	32	11.8	11.8	5	49
19	Oct-11-2005	284	32	10.7	11.6	5	22
20	Oct-08-2005	291	27	11.3	11.3	5	49
21	Nov-15-2005	319	27	9.1	10.6	5	900
22	Nov-22-2005	326	25	10.4	10.4	10	1600
23	Nov-29-2005	333	21	8.1	10.3	10	34
24	Dec-06-2005	340	22	10.3	10.3	10	38

* A sample of 0 NTU turbidity was also placed with each turbid sample as control

solution to generate desired turbidity levels of 5, 10, 20 and 30 NTU for SODIS application. HACH, Model 2100AN turbidity meter was used for turbidity measurements and temperature and pH were measured using Sension 156 HACH, portable multi-parameter meter. The water samples with different turbidity were placed on a silver metallic corrugated sheet which was fixed on the IEER's rooftop. The experiments were started with the first sample drawn at 9:00 in the morning, followed by the 2nd, 3rd, 4th and 5th samples obtained at 1.5 hours intervals at 10:30, 12:00, 13:30 and 15:00 respectively. For all experiments, the last sample was collected at the sunset. For further details of sample collection, storage and analysis, interested readers are referred to Haider *et al.* (2014) [13].

The climate data for sunshine hours and atmospheric temperature were acquired from the *WeatherSpark* website (http://weatherspark.com) [36]. This data was observed at Allama Iqbal International Airport, Lahore, Pakistan located at an aerial distance of 7 Km from the study area. The experimental work was carried out for 3 consecutive years (i.e., September 2005 to May 2008). The environmental data listed in Table 2 shows that the maximum possible climatic variations were captured by performing the experiments around the year. In Table 2 the SSH range between 1.5 and 10 per day in the study are depending on the cloud cover conditions. This effect has been estimated in terms of *OKTAS*, i.e., a universally used meteorological term for measuring the cloud cover as 1/8th of the sky. For example, a value of 0 represents clear sky and an *OKTAS* value of 8 corresponds to fully covered clouds [37].

Estimating Solar Radiations: Intensity of solar radiations can be estimated with the help of empirical methods. Oates *et al.* (2003) stated that if the ratio between the total average daily solar radiation (I_{ad}) and the average hourly solar intensity (I_{ah}) is determined; then knowing the I_{ad} from data sources, I_{ah} can be estimated [11]. Haider *et al.* (2014) used this approach and the average, minimum and maximum I_{ah} values during the sampling days are shown in Figure 2. The figure describes that even the minimum intensity of solar radiations are higher than the desirable solar radiations (i.e., 500 W/m^2). At least 4 hours in a day the values are higher than the desired (even at 4-*OKTAS*) and the average exposure durations are 6 hours.

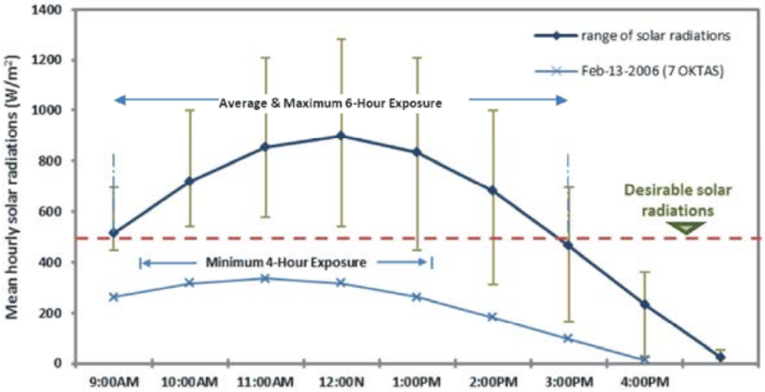

Fig. 2: Minimum, maximum and average hourly solar radiations for the 24 sampling days spanned over a period of 3 years (2005-2008) in Lahore (Source: Haider *et al.* 2014)

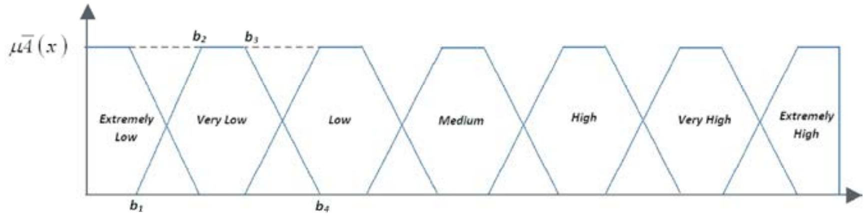

Fig. 3: Standard trapezoidal membership functions used in this study; For example, b_1, b_2, $b_3$and b_4 are used to define the ranges of fuzzy numbers for 'very low' turbidity, *OKTAS*, or exposure period

These results manifest that sufficient solar radiations are available in the study area for effective SODIS process. Details calculations can be found in Haider *et al.* (2014) [13].

Fuzzy Rule-Based Modeling (FRBM): To deal with uncertainties identified in the introduction section, the universe of discourse (UOD) for the significant model parameters are linguistically established using the knowledge of previous studies, experimental results of this study and expert knowledge. These uncertainties are addressed in this research with the help of fuzzy set theory which was first developed by Zadeh (1978) to logically integrate human reasoning with the decision making [38]. The models based on linguistically defined parameters can deal with the qualitative and imprecise/uncertain knowledge in the form of *if-then* rules [39], e.g., '*If antecedent proposition, then consequent proposition'*. The expression is generally articulated as inference such that if the fact (antecedent) is known, then the conclusion (consequent) can be inferred [40]. For details, the readers are referred to Ross (2004) [40].

The UOD of fuzzy trapezoidal membership functions used in this study defined with the elements *(a, b, c and d)*are shown in Figure 3. An example can be set as, *'If turbidity is medium and the OKTAS is low, then the exposure period is medium'*. A total of 90 rules are established, i.e., 30 rules each for 2, 3 and 4 log-reductions.

The linguistically defined model can deal with the qualitative and imprecise or uncertain information in the form of *if-then* rules such as [39]:

$$R_i\text{: If } X \text{ is } A_i \text{ then } Y \text{ is } B_j i = 1, 2, \ldots, L; j = 1, 2, \ldots, N \qquad [1]$$

Where R_i is the rule number i, X is the input (antecedent) fuzzy variable, A_i is a fuzzy subset corresponding to an antecedent linguistic constant (one of L in set A), Y is the output (consequent) fuzzy variable and B_j is a fuzzy subset corresponding to a consequent linguistic constant (one of N in set B).

A typical fuzzy rule-based model consists of four components: fuzzifier, rule-base, inference engine and defuzzifier. The fuzzifier directs the degree of membership of a crisp input into a fuzzy set with the help of membership functions. The rule-base describes the fuzzy relationships between the input and the output variables. Subsequently, the output is determined based on the degree of membership specified by the defuzzifier. For inferencing the exposure period FRBM is performed using fuzzy logic toolbox in MATLA Band for defuzzification center of area method (SOM) is used.

RESULTS AND DISCUSSIONS

Experimental Results and Analysis of Variance: Experiments were performed on the water samples with 5, 10, 20 and 30 NTU to obtain six sets of data on different days (refer to Table 2). Turbidity, fecal coliforms, bottle temperature, atmospheric temperature and pH were measured for all the samples. The pH values were found between 6.5 and 7.5 which meet the drinking water quality guidelines. The bottle temperature varied between 18°C and 44°C correspond to the average atmospheric temperature range of 13°C to 39°C. During experimental phase, significant variations in cloud cover conditions were observed from clear sky (0-*OKTAS*) to 90% of the cloud cover (7-*OKTAS*).

The results of FCs measured at varying *OKTAS* conditions for the 5 samples each turbidity level are shown in Figure 4 (a-e). Figure 4 shows that Fcs' inactivation significantly depends on both the cloud cover and turbidity. For instance, the comparison between 0 NTU and 5 NTU shown in Figure 4 a & b reveals that 3 log-reduction of FCs was observed at *2-OKTAS* with an exposure period of 3 hours. Conversely, the sample with 0 NTU took 4.5 hours for the same removal under *4-OKTAS*. Similar results were obtained at 10, 20 and 30 NTU turbidity levels.

To identify significant factors affecting SODIS process, Haider *et al.* (2014) carried out the analyses of variance (ANOVA) and 2^3 factorial designs to evaluate the possibility of significant interactions between the parameters. They found turbidity and *OKTAS* as the significant factors affecting SODIS with very low *P-values* of 0.0027 and 0.00012; while the bottle temperature was found be an insignificant factor with a high *P-value* of 0.21. These results were consistent with the findings of a study conducted by McGuigan *et al.* (1999) [10] mentioning temperature higher than 40°C are required for thermal activation of pathogens.

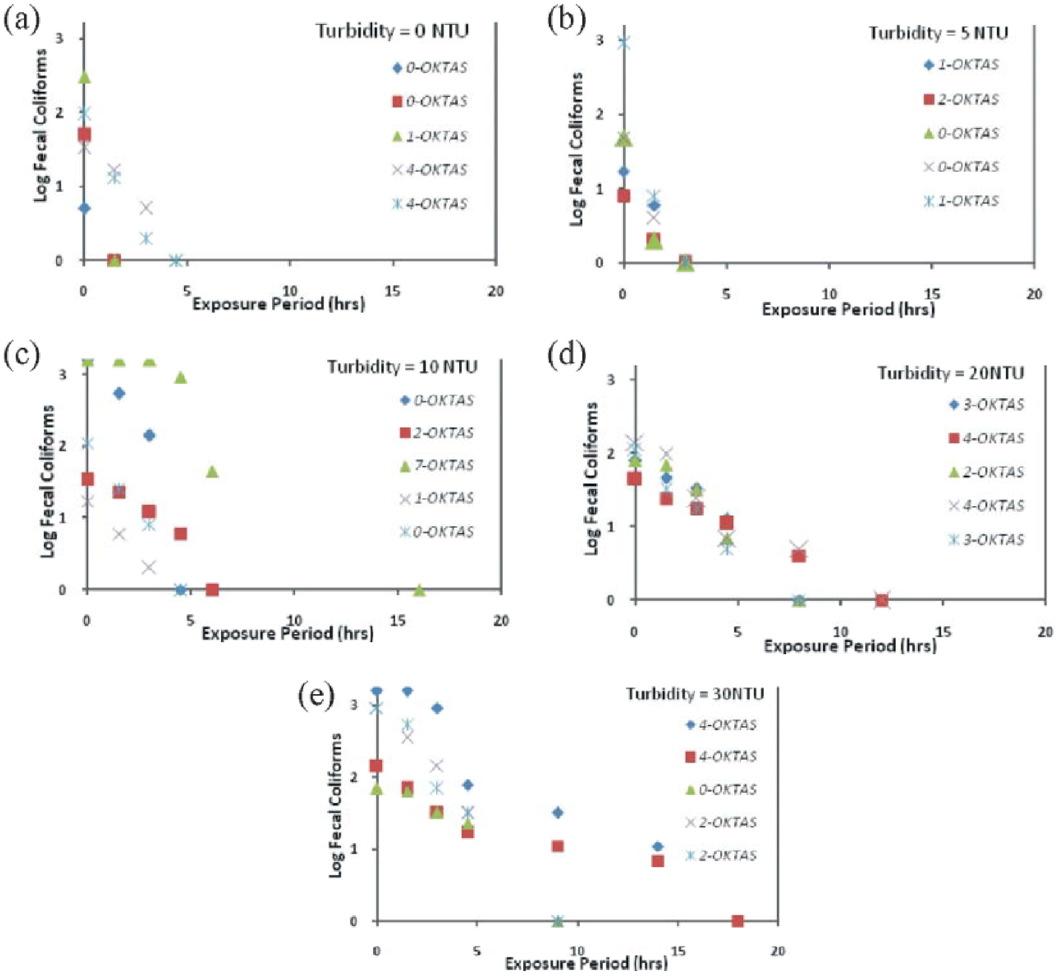

Fig. 4: Fecal coliforms observed log values at different turbidity and cloud cover *(OKTAS)* conditions [13]

Table 3: Universe of Discourse defined for estimating exposure period using FRBM

Universe of Discourse (UOD)	Turbidity (NTU)	*OKTAS*	Exposure Period Polluted water[a]	 Highly polluted water [b]	 Extremely polluted water[c]
Extremely low (EL)	0 - 3	0 – 0.5	1.0 -2.0	2.0 – 3.0	3.0 – 4.5
Very low (VL)	2 -5	0.25 – 1.0	1.5 – 3.5	2.5 – 5.0	4.0 – 6.5
Low (L)	4 - 7	0.75 – 2.0	3.0 – 5.0	4.5 – 7.0	6.0 – 8.5
Medium (M)	6 - 12	1.75 – 3.25	4.5 – 6.5	6.5 – 9.0	8.0 – 10.5
High (H)	10 -16	3.0 – 5.0	6.0 – 8.0	8.5 – 11.0	10.0 – 13.0
Very high (VH)	14 - 22	4.5 – 6.5	7.5 - 10	10.5 – 13.5	12.5 – 16.0
Extremely high (EH)	20 - 30	6.0 – 8.0	9.5 - 12	13.0 – 16.0	15.5 – 19.0

[a]2 log reduction; [b]3 log reduction; [c]4 log reduction

Exposure Period Assessment under Uncertainty: Table 3 presents the universe of discourse defined for the inputs (i.e., turbidity and OKTAS) and the output (i.e., exposure period) to deal with different uncertainties due to data limitations, measurement errors and vagueness in expert knowledge. In addition to the measurement errors in turbidity and FCs estimation, these parameters may significantly vary at the source water. Certainly, using absolute values based on limited number of samples examined may be misleading. Similarly, OKTAS values in terms of SSH reported by the metrological stations also vary during an hour. These uncertainties are addressed in this study with the help of FRBM. Due to the experimental conditions of the study, the UOD defined in table 3 is applicable to the atmospheric temperatures higher than 10°C and the range of FCs concentration between 1 to >1600 MPN/ 100mL. However, 4 log reductions represent highly polluted raw water, probably drawn from surface water sources in developing countries. Such water may contain higher turbidity levels as well. The last values of exposure period in Figure 4 shows the maximum possible 3 or 4 log-reduction 3 or 4 correspond to 99.99% removal are against the undetectable FCs in the SODIS samples.

For practical application of this research, the surface viewers developed for 2, 3 and 4 log-reductions are shown in Figure 5a-c. In this study, the UOD is intuitively defines based on the results; for example, FCs can be completely inactivated through SODIS with the same exposure period for samples with 0, 10 and 20 NTU turbidity due to the difference in clod cover conditions, i.e., *OKTAS* values of 4, 0 and 1 respectively. Nevertheless, initial concentration of FCs can change the required exposure. In this regard, the term '*polluted water'* corresponds to 2 log reduction, '*highly polluted water'* to 3 log reduction and *'extremely polluted water'* to 4 log reductions required to completely inactivate FCs. It is important to be noted here that the term '*polluted water'* in this research is designated to FCs only and not the samples with higher turbidity. A polluted raw water (i.e., 2 log reductions required) with 5 NTU turbidity can achieve complete removal of FCs through 3 hours of exposure under lower *OKTAS*. On the other hand, an 'extremely polluted water' sample with 30 NTU and 4 *OKTAS* (i.e., 50% cloud cover) would require 16 hours of exposure period.

The surface viewers presented in Figure 5 a-c are applicable for 0 to 30 NTU turbidity range and an atmospheric temperature of 10°C. These surface viewers will help to select a suitable exposure period for the entire range of cloud cover condition varying from full sunny to overcast. To validate the developed FRBM, the results shown in Figure 4 are compared with the model simulations in Figure 6. Figure shows a close agreement between the measured values and the model results with high R-squared value of 0.9154.

In order to effectively implement the developed model and to facilitate the end users, municipalities should categorize the source water as 'polluted', 'high polluted' and 'extremely polluted'. Secondly a colour toning bar would be useful to select an appropriate turbidity level. Similarly, pictorial information showing varying cloud cover conditions correspond to different OKTAS levels will also support the end user to practically use these surface viewers.

An effective SODIS application in rural areas of developing countries can reduce the cost of the other alternative disinfection methods such as boiling, use of hypo-chlorites, or mixed oxidant gases [41]. Associated costs and health risk in case of chemical disinfection methods have been well reported in literature [42]. For areas with distinct monsoon season, the SODIS should be applied with careful supervision by identifying the effective period for SODIS application during the year. Estimating solar radiations whether these are available for 500 W/m^2 or higher for 3 to 5 hours/ day with the help of method prescribed by Haider *et al.* (2014) is recommend before implementing SODIS as a regular disinfection method at household level. Though SODIS can be applied under overcast conditions with longer exposure periods, it might not be a sustainable disinfection method for the areas having full cloud cover spanning over days. For such areas, the feasibility of other cost effective methods at household or system level should be explored; however, SODIS can replace these methods during the favourable months of a year to save cost of chemicals and to minimize health risks.

CONCLUSIONS AND RECOMMENDATIONS

For small or rural water supplies in developing countries, SODIS is a sustainable disinfection method requiring minimal operational cost and skills. The methods significantly depends on level of turbidity and cloud cover conditions, however, the impact of atmospheric temperature less than 40°C is not significant on the efficiency of the SODIS process.

Estimating exposure period for a given value of turbidity, cloud cover conditions and number of coliforms is a tedious process which can be affected due to several types of uncertainties associated with the measurement errors, limited number of experiments not covering entire range of environmental and weather conditions and use of climatic data for average conditions. In this research fuzzy set theory is employed to address these uncertainties.

A fuzzy rule based model is developed and validated to estimate required exposure period for a turbidity range of 0 to 30 NTU, 0 to 100% cloud cover conditions (i.e., 1 to 8 OKTAS) and 2, 3 and 4 fecal coliforms log-reductions. Comparison between the measure values and model simulations show a strong correlation with R-squared value of higher than 0.9.

Using fuzzy logic toolbox in MATLAB, surface viewers are developed for polluted, highly polluted and extremely polluted surface or ground water correspond to 2,3 and 4 log reductions. These viewers can facilitate the end user with simple application of SODIS supported by the colour toning scheme and pictorial information for selecting an appropriate turbidity level and varying cloud cover conditions respectively.

SODIS needs long exposure periods in overcast conditions, therefore it might not be a sustainable disinfection method for the areas having such conditions sustaining for days. In these areas, the feasibility of other suitable methods can be explored at household or

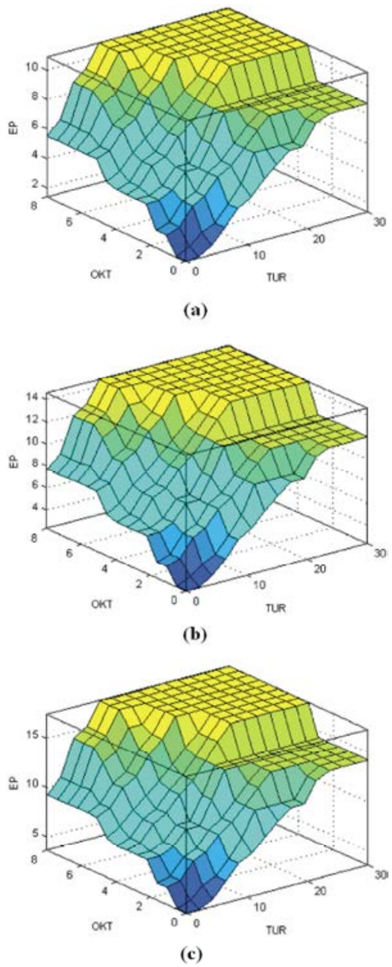

Fig. 5: Surface viewers developed through fuzzy logic tool box in MATLAB, (a) polluted water, (b) highly polluted water and (c) extremely polluted water

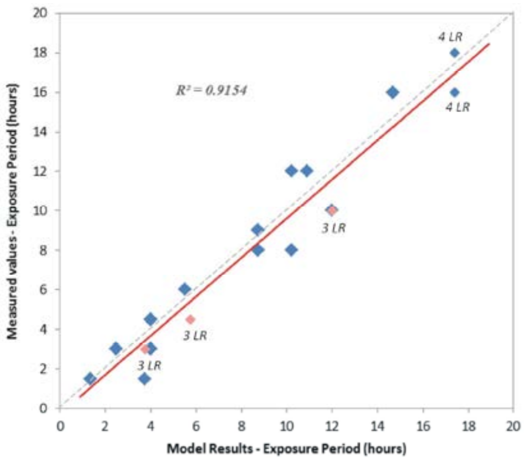

Fig. 6: Comparison between measure values of exposure period and FRBM simulation results, LR represented log-reduction

community level. Validation of the developed model is also recommended at other locations with different environmental conditional.

ACKNOWLEDGEMENTS

Experimentation work was carried out at the Institute of Environmental Engineering and Research (IEER), University of Engineering and Technology (UET), Lahore, Pakistan. Support of the IEER laboratory staff in sample collection and analysis is acknowledged.

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