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Understanding the effect of socio-economic characteristics and psychosocial factors on household water treatment practices in rural Nepal using Bayesian Belief Networks

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ABSTRACT

About 20 Million (73%) people in Nepal still do not have access to safely managed drinking water service and 22 million (79%) do not treat their drinking water before consumption. Few studies have addressed the combination of socio-economic characteristics and psychosocial factors that explain such behaviour in a probabilistic manner. In this paper we present a novel approach to assess the usage of household water treatment (HWT), using data from 451 households in mid and far-western rural Nepal. We developed a Bayesian belief network model that integrates socio-economic characteristics and five psychosocial factors. The socio-economic characteristics of households included presence of young children, having been exposed to HWT promotion in the past, level of education, type of water source used, access to technology and wealth level. The five psychosocial factors capture households' perceptions of incidence and severity of water-borne infections, attitudes towards the impact of poor water quality on health, water treatment norms and the knowledge level for performing HWT. We found that the adoption of technology was influenced by the psychosocial factors norms, followed by the knowledge level for operating the technology. Education, wealth level, and being exposed to the promotion of HWT were the most influential socio-economic characteristics. Interestingly, households who were connected to a piped water scheme have a higher probability of HWT adoption compared to other types of water sources. The scenario analysis revealed that interventions that only target single socio-economic characteristics do not effectively boost the probability of HWT practice. However, interventions addressing several socio-economic characteristics increase the probability of HWT adoption among the target groups.

1. Introduction

Access to potable water is still a global challenge (WHO & UNICEF, 2017b). About 2.1 billion people, mostly in low and middle income countries (LMICs), are still without "improved drinking water source that is located on premises, available when needed, and free from faecal and priority chemical contamination" (WHO & UNICEF, 2017a). These unsafe conditions cause a high number of water-related diseases that have contributed to 9.1% of the global disease burden and have been responsible for the deaths of 1.3 million people in 2015, most of whom are children below the age of 5 and located in LMICs (Collaborators, 2017).

Household water treatment (HWT), which treats water at the point of use such as boiling and ceramic filtration, is one possible means to tackle the challenge of non-potable water at household level (Clasen, 2009). However, studies have shown that, although necessary and potentially having a positive health impact, households do not regularly use HWT (Brown and Clasen, 2012). This reduces its potential health benefits (Hunter et al., 2009).

Psychology concepts or frameworks have been used to understand why people use or do not use HWT, for example Risk – Attitude – Norm – Ability – Self-regulation (RANAS) model (Mosler, 2012), the health belief model (Rainey and Harding, 2005), or Integrated Behavioural Model for WASH (IBM-WASH) (Dreibelbis et al., 2013). In this paper, we used the RANAS to model this behaviour due to its high capability of explaining WASH-related behaviour and the convenience to adapt the

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Fig. 1. Location of the study area in mid and far-western Nepal, drawn using ArcGIS (ESRI, 2011).

RANAS structure to a simple causal structure. RANAS, as also revealed by other behavioural studies, argues that the socio-economic characteristics of people (called contextual factors in RANAS) influence behaviour in two ways: directly (Ball et al., 2009; Businelle et al., 2010; Contzen and Mosler, 2015) and indirectly through the behavioural determinants (i.e., psychosocial factors) (Gecková et al., 2005; Martinez et al., 2018; Rodriguez et al., 2014).

Previous studies have included socio-economic characteristics and psychosocial factors in their analysis of explaining the use of HWT. A study in Sri Lanka, e.g., showed that socio-economic factors, such as education, WASH promotion, and type of water source drove the households' perception of risk, and higher perception of risk led to a higher likelihood of households treating water (Nauges and Berg, 2009). However, they only used one psychosocial factor: perceived risk, though we know there are other psychosocial factors that also play a role in shaping human behaviour, such as *norm* or *ability*. Recent RANAS studies have further analysed the combination of socio-economic and psychosocial factors, using hierarchical regression analysis to predict handwashing behaviour (Seimetz et al., 2016) and the cleaning of water storage containers (Stocker and Mosler, 2015).

However, in spite of the clear need for a systems-level approach, i.e., analysing all interacting variables within one system, that considers the influence of socio-economic characteristics on adoption behaviour of HWT via psychosocial factors, this perspective has often been ignored and remains to be explored (Daniel et al., 2018; Dreibelbis et al., 2013). Therefore the motivation of this study is to analyse the interactions between socio-economic and psychosocial factors, to visualize these interactions in a conceptually causal manner, and accordingly, to model them in order to quantitatively predict the adoption of HWT.

Bayesian belief networks (BBN) can model the interaction between variables that are causally linked (or theorized to be so) in a probabilistic manner. A BBN contains a directed acyclic graph (DAG), showing the dependencies between variables (called "nodes" in BBN) based on conditional probability tables (CPTs), which represent the strength of such relationships between the parent nodes (i.e., where the arrow originates or *the cause*) and child node (i.e., where the arrow ends or *the effect*) (Pearl, 1988). For example, a Bayesian network could represent the probabilistic relationships between diseases such as diarrhea or common flu and a symptom such as vomiting. Given data, the network can be used to impute the probabilities of the vomiting caused by diarrhea and flu independently, which are then documented in the CPT corresponding to the node of vomiting.

BBN offers advantages over other methods, such as regression analysis or agent-based modelling, by 1) visualising a causal interpretation of a complex system, 2) stimulating stakeholder participation, 3) integrating expert judgement to tackle uncertainties and unknown data, 4) integrating quantitative and qualitative information, and 5) performing both predictive and diagnostic inference (Barton et al., 2012; Cain, 2001). Despite its many advantages, very few studies related to WASH, such as understanding hand pump functionality in Africa (Cronk and Bartram, 2017; Fisher et al., 2015), have used BBN models. This approach therefore remains underexplored in understanding WASH-related behaviour (e.g., HWT or handwashing), as found in two reviews of BBN applications in water science and management (Landuyt et al., 2013; Phan et al., 2016).

We present a WASH related cross-sectional survey of rural communities in the mid and far-western regions of Nepal. An analysis of the interactions between socio-economic characteristics and psychosocial factors, and the impact of these interactions on the adoption of HWT through the lens of the simplified RANAS model. BBN was used to estimate the probability of HWT adoption, while considering the combinations of socio-economic and psychosocial variables.

2. Methods

2.1. Study setting and data source

In October 2014, a cross-sectional study was conducted during which 512 households were surveyed within five Village Development Committees (VDCs), which are the smallest administrative unit in Nepal. The five VDCs were located in different districts in two provinces: (1) Province Karnali Pradesh: Jarbuta VDC in Surkhet district, Nepa VDC in Dailekh district, and Sima VDC in Jajarkot district; and (2) Province Sudurpashchim Pradesh: Birpath VDC in Achham district and Pahalmanpur VDC in Kailali district (Fig. 1).

Helvetas Swiss Intercooperation, a non-profit organization based in Switzerland, sought this research collaboration to rigorously investigate WASH practices within its service area in the five districts described above. For the study of WASH practices, data collection involved semi-structured face-to-face household interviews. The questionnaires were translated into Nepali, back-translated into English, and reviewed for accuracy. A pilot test was conducted before the field research. Informed consent was obtained from all participants prior to the interview. This baseline study was part of a WASH project initiated by Helvetas Swiss Intercooperation which was approved by Department of Water supply and Sewerage Nepal.

Study households were randomly selected for enrolment in a two-step randomization process: first, within each VDC, wards (sub-level of

Table 1
Descriptive statistics of behavioural determinant factors, i.e. psychosocial factors. M = mean, SD = standard deviation.

Determinant factors		Example questions	Scales	M(SD)
Risk	Vulnerability	How high do you feel is the risk that you will get diarrhea if you drink untreated water?	1–5	2.51 (1.07)
	Health knowledge	What are the causes of diarrheal diseases?	1-5[a]	1.32 (0.77)
	Severity on life	Imagine you have diarrhea, how severe would be the impact on your daily life?	1–5	4.16 (0.63)
	Severity on a child under 5 years	Imagine your child below 5 years has diarrhea, how severe would be the impact on his life and development?	1–5	4.15 (0.54)
Attitude	Health benefit	How certain are you that always treating your water will prevent you from getting diarrhea?	1–5	2.98 (0.93)
Norm	Descriptive	How many of your neighbours treat their water?	1–5	1.44 (0.83)
	Injunctive	People who are important to you, how do they think you should always treat your water before consumption?	1–5	2.44 (1.07)
	Personal	How strongly do you feel an obligation to yourself to always treat your water before consumption?	1–5	3.03 (0.97)
Ability	Action knowledge	Can you explain to me the procedures of the different methods for water treatment?	1-5[a]	2.13 (1.22)

[a] For *health knowledge*, the scale is based on the correct causes mentioned by the respondents; and for *action knowledge*, the scale is based on the correct HWT procedures explained by the respondent. See Table S4 for more information.

VDC) were randomly selected after a participatory social mapping of the VDC with community members based on the population of the wards. Second, households were randomly selected within the selected wards through a transect-walk and enrolment of every two or three houses. The target participants were women who are the primary caregivers in the households. The questionnaire covers household information, information on water access, WASH knowledge (questions on sanitation and hygiene specifically), perception, water related behaviour, health status, and market information. A five-item *Likert scale* was used to measure each behavioural determinant factor (Table 1). Socio-economic characteristics were measured on a nominal scale (Table S3). The respondent's answer to this question was used as the outcome variable: "'Do you use any method to treat your drinking water?".

2.2. A conceptual model of HWT adoption

2.2.1. RANAS psychosocial factors

The RANAS model consists of five psychosocial factors: *risk*, *attitude*, *norm*, *ability*, and *self-regulation* (Fig. 2) as described in Mosler (2012). *Risk* factors indicate an individual's understanding and perception of health risk. *Attitude* factors represent a person's belief towards the behaviour, such as positive or negative opinions about the costs and benefits. *Norm* factors represent which behaviours are perceived to be normal and abnormal. *Ability* factors relate to an individual's perception in his or her ability to execute the behaviour. Finally, *self-regulation* represents factors that are responsible for the continuation and maintenance of certain behaviour, such as commitment. More details can be found in S1.

Since RANAS requests the information at the sub-factor level of psychosocial factors (Fig. 2 and Table S1), Principal Component Analysis (PCA) on the sub-factors was performed to simplify the BBN structure and the first principle component, where possible, was used to represent each RANAS factor. The data were analysed in IBM SPSS 23. PCA was conducted only on the two psychosocial factors: *risk* and *norm*. The PCA on factor *risk* yielded two dominant components: Component 1, named *perceived severity*, was mostly influenced by variables *perceived severity on life* and *perceived severity on a child under five years*, and Component 2, named *perceived infection probability*, was mostly influenced by *perceived vulnerability* and *health knowledge*. The PCA on the sub-factors *norm* yielded one dominant component (detail in S2). The component scores were then divided into three levels based on the score: one-third of the lowest score as "low", the next one-third as "moderate", and the rest as "high". The "new factors" were then used in the BBN analysis (see S2).

We lost information on the sub-factors of *attitude*, *ability* and *self-regulation* due to coding error (Table S1). Therefore PCA was not be conducted on these variables. The psychosocial factor *attitude* was represented by its sub-factor "beliefs about health benefits" and the factor *ability* was represented by the sub-factor "how-to-perform knowledge" (action knowledge). We scaled these factors into the three categories: "low", "moderate" and "high", in order to keep the CPTs of the BBN model parsimonious and understandable (see S2). We had to further simplify the model by removing the RANAS factor *self-regulation* from the analysis because only about 30% of the total cases had answered to the corresponding question (Table S1). Such simplification does not

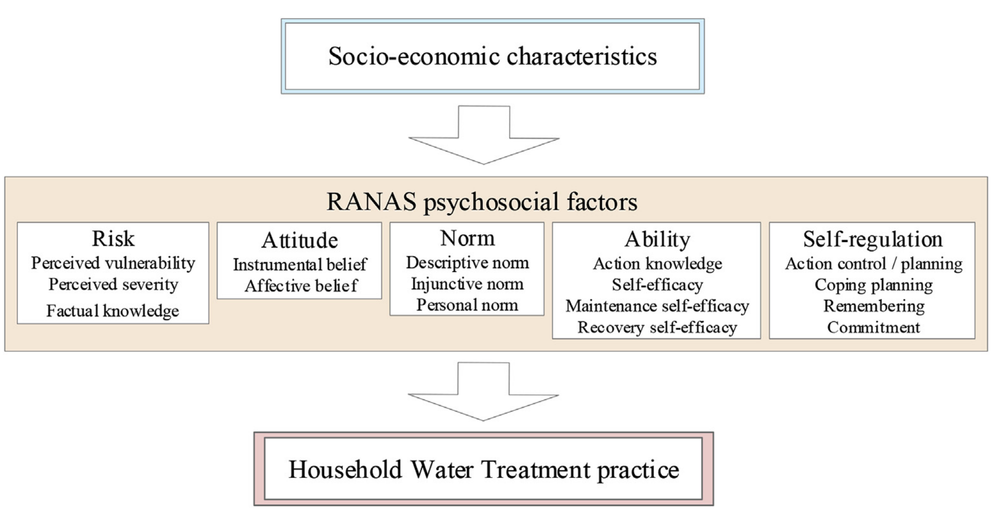

Fig. 2. Conceptual model adapted from Risk – Attitude – Norm – Ability – Self-regulation (RANAS) model for constructing the BBN structure. Adapted from (Mosler, 2012).

undermine the conclusion that are drawn later. That is because self-regulation is hard to measure in households who do not perform the behaviour, i.e., we had only 22% respondents who practiced HWT (Lilje and Mosler, 2018).

2.2.2. Socio-economic characteristics

Eight socio-economic characteristics were identified from literature that may influence the psychosocial factors (Table S3): 1) *level of education* (Fotue Totouomet et al., 2012; Nauges and Berg, 2009), 2) *WASH* (i.e., water, sanitation, and hygiene in general) or 3) HWT (i.e., HWT knowledge and practice specifically) *promotion activities* (George et al., 2016; Mosler et al., 2013), 4) *type of water source* (Casanova et al., 2012; DuBois et al., 2010), 5) *Wealth level* (Luby et al., 2004; Opryszko et al., 2010), 6) *logistic access* (DuBois et al., 2010; Goldman et al., 2001), 7) *presence of sick children* and 8) *presence of children under the age of 5* (Christen et al., 2011; Freeman et al., 2012).

We performed PCA to create *relative wealth level* using information on household assets (Table S2). The first component of PCA was assumed to measure the wealth level of the respondents (Houweling et al., 2003). The respondents were then divided into three groups: poor (40%), middle income (40%), and rich (20%); according to their scores (Vyas and Kumaranayake, 2006).

For the analysis, we removed 61 data cases that did not contain information on the current practice of treating water. Thus, a total of 451 cases from 512 households were analysed. The answer “do not know” was coded as an empty value to simplify the categories in the analysis. Furthermore, we categorized the study locations in our study into *easy logistic access* (Surkhet and Kailali) and *difficult logistic access* (Accham, Jajarkot, and Dailekh).

2.2.3. Performing the BBN model

Four aspects were considered when building the BBN structure: statistical relationship between the socio-economic factors and psychosocial factors, the complexity of the model (i.e., number of variables and categories/states), conformity of inferred relationships with what are reported in literature, and model performance (Bae and Chang, 2012; Cain, 2001; Chen and Pollino, 2010; Marcot et al., 2006).

The one-to-one relationships (nonparametric chi-square) tests between each households' socio-economic characteristics and ‘principal’ psychosocial factors were performed to assess potential causal relationships between them (see Fig. S4). However, connecting all significantly associated variables may result in a more complex model, in which case even a statistically significant relationship may not represent a true causal relationship. Therefore, more nodes should only be added and connected thereby increasing the sizes of CPTs, when it result in a significant improvements in the BBN model performance (Marcot et al., 2006). Thus, in this study, we considered the model performance (i.e., the comparison of the results of validation test) as the most important consideration. In order to simplify the BBN structure, we only considered the indirect pathways of socio-economic characteristics influencing the adoption of HWT via psychosocial factors, using an assumption that socio-economic factors rarely influence behaviour directly.

We used the *Genie 2.2* (www.bayesfusion.com) software package to implement the BBN analysis. The expectation maximization (EM) algorithm within the software was used to estimate and populate the CPTs (i.e. calibrated) in a BBN based on the collected survey data set (Druzdzel and Sowinski, 1995). This algorithm is considered to be effective, especially when data sets are incomplete (Do and Batzoglou, 2008).

The ten-fold cross-validation was used, using the same software, to judge how robust calibrated CPTs are, by first calibrating them on a subset of data and using the calibrated model in prediction mode on the remaining data (not used in model calibration) to judge model's performance. In our case, 90% of the dataset was randomly selected to impute the CPT and the remaining 10% was then used to ‘validate’ the performance of the calibrated model. Since the calibration and validation subsets were randomly selected, the process was repeated 10 times and the average of validation performances was taken as the cross ten-fold cross validation score. Another performance that was considered was Receiver Operating Characteristics (ROC). The ROC graph plots the ‘sensitivity’ on the *Y* axis and *false positive* on the *X* axis. The value of the area under the ROC curve (AUC – Areas Under Curve) is used to assess model performance. The closer the AUC value is to 1, the better is its performance (higher sensitivity and lower false positives) (Greiner et al., 2000).

Parameter sensitivity analysis of the input node was performed to identify the nodes that most influence the output node. We utilized the algorithm within the Genie software which calculates the effect of small changes in the CPT of each node on the output node.

Finally, we simulated the interventions (scenario analysis) by exploiting the predictive strength of BBN, i.e., Bayesian inference. Updating the beliefs of socio-economic nodes (outer layer) updates, first, the likelihood values of psychosocial nodes (intermediate layer), and thereafter the outcome node. For example, updating *HWT promotion* to 100% “yes”, increased the probability of four psychosocial nodes being “high” that were connected to it: *severity, infection probability, attitude*, and *ability*, then increased the probability of using HWT from 18% to 20% (Figs. S1–S2).

3. Results

3.1. Descriptive analysis of the study area

The questionnaire results show that only 22% of all the respondents treated their water. About 57% of the respondents obtained water from piped community taps and 27% from a tube well. About half of the respondents (51%) had at least one child below the age of 5. Only 10 cases of a household having a family member experiencing diarrhea in the last two days were reported during the survey. Forty-five percent of the respondents reported having no education. Detail information can be found in Table S3. Means and standard deviations of the psychosocial sub-factors are provided in Table 1.

3.2. Bayesian belief network structure and model

3.2.1. Lay-out of the BBN model

Fig. 3 showed the final structure that had the best model performance, while it kept the number of links between the socio-economic characteristics and psychosocial factors to a minimum. The BBN model predicted a use of HWT of 18% considering information in all nodes, which was slightly different from the real percentage of HWT use (22%). We did not include variable *diarrhea cases* in the model because it did not have a statistically significant relationship with any of the psychosocial factors and the proportion of diarrhea cases was only 2.4% in the dataset. Furthermore, we included HWT promotion rather than WASH promotion in the model since it had a more statistically significant relationship with other psychosocial factors (Fig. S4).

3.2.2. Validation test

The overall model accuracy to predict the output was 83.65% (STD = 0.35%). Its success in predicting the output “no” (true negative or ‘specificity’), which means that a household did not treat its drinking water, was 93.33% (STD = 0.43%) and predicting the output “yes” (true positive or ‘sensitivity’) was 49.19% (STD = 1.51%). Moreover, the area under the ROC curve (AUC) was 0.85 (STD = 0.005). The closer the AUC value is to 1, the better is its performance (higher sensitivity and lower false positives). The result, thus, suggests that the model performance was *good* in predicting the output (Greiner et al., 2000), i.e., it could distinguish between the *adopters* and *non-adopters* of HWT sufficiently well.

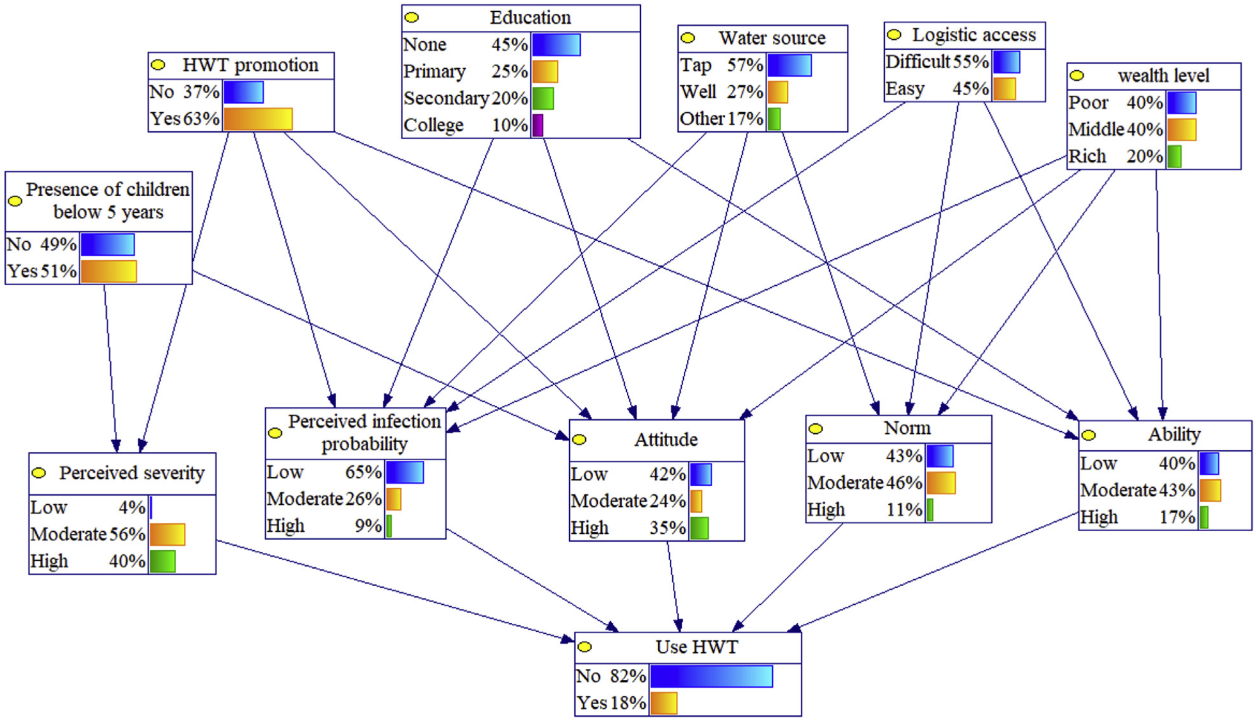

Fig. 3. The compiled BBN model of household water treatment adoption in rural Nepal. The bars in each node show the probability that a node is in a certain state.

3.2.3. *Parameter sensitivity analysis*

Fig. 4 shows the maximum values of the derivatives of posterior probability distributions of the output node, taken in relation to the entries of the CPT of a node. For example, node *education* had a corresponding value of seven percent, which means that there was one entry in the prior probability table of education, which when perturbed by one percent of its current value caused a maximum seven percent change in the probability of HWT adoption. Changing other entries in that node gave derivative values lower than 0.07.

The sensitivity analysis shows that among socio-economic characteristics, *education* was the most sensitive node, followed by *wealth level*, and *received HWT promotion* in the past. The nodes *severity* and *norm* were the most sensitive nodes among psychosocial factors. However, from the sensitivity analysis, we considered that there were no single highly sensitive socio-economic or psychosocial nodes that highly affect the output node.

3.2.4. *Effect of updating single node on the output node*

The effect of updating the belief (i.e., changing the value of input nodes) of a single node on the output node is presented in Table 2. For example, setting the type of water source to 100% = "Tap" to 100%, updates the probability of using HWT to 19% (from 18% in the baseline). No single factor, socio-economic or psychosocial, on its own increased the probability of HWT adoption to at least 50% (Updated $P_{use\ HWT}$ = yes; Table 2). Among the socio-economic characteristics, *education* was the most influential node, followed by *wealth level* and

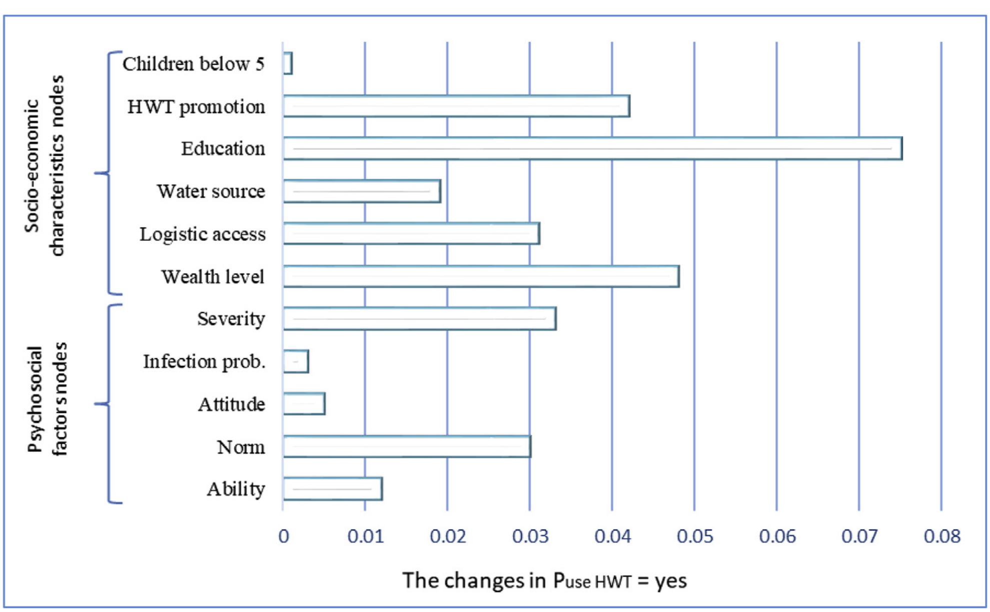

Fig. 4. Sensitivity analysis of individual nodes on the output node.

Table 2
Changes in posterior probability of positive outcome (using HWT) by individual nodes.

Nodes	Updated $P_{use\ HWT}$ = yes (%)[a]				$\Delta P_{(HWT=yes)}$ (%)[b]
Socio-economic characteristics					
Type of water source	Tap 19	Tube well 17		Other 16	3
Presence of children under 5 years	No 18		Yes 18		0
Receive HWT promotion	No 15		Yes 20		5
Education	None 15	Primary 19	Secondary 20	Higher 24	9
Logistic access	Easy 20		Difficult 16		4
Wealth level	Poor 19	Middle 16		Rich 21	7
Psychosocial factors					
Perceived severity	Low 8	Moderate 20		High 16	12
Perceived infection probability	Low 17	Moderate 19		High 22	5
Attitude (certainty about health impact)	Low 11	Moderate 23		High 23	12
Norm	Low 10	Moderate 23		High 31	21
Ability (action knowledge)	Low 9	Moderate 22		High 29	20

[a] The value under each category is the updated probability of the output node given the belief of that node. The baseline probability was 18% (Fig. 3).
[b] ΔP is the difference between the lowest and highest value of the updated probability of HWT adoption being "yes" in %.

whether the respondents *received HWT promotion* or not, while the *presence of children under 5 years* did not change the likelihood of HWT adoption (see the change $\Delta P_{use\ HWT}$ = yes in Table 2). Another observation is that easily accessible areas such as Kailali, had a higher probability of using HWT.

The psychosocial factors *norm* and *ability* played an important role in influencing the likelihood of using HWT. Moreover, the more households *perceived severity* and *infection probability*, the higher was their probability to use HWT. Additionally, the psychosocial factors realizing the *health benefits of doing HWT*, *social pressure*, and *know how-to-perform HWT* all significantly influenced the adoption of HWT.

3.3. Scenarios analysis to increase the probability of HWT adoption

Bayesian inference was used only to simulate potential interventions but also to understand how the system works. For example, updating node *education*. The more educated the person is, the higher level of *ability* and *attitude* obtained. Surprisingly, the analysis showed that *education level* had an inverse effect on *perceived infection* probability, with more education resulting in a lower level of *perceived infection* (Fig. S3). Nevertheless, *education* still had an overall positive effect on HWT adoption (Table 2).

Because HWT adoption can mainly indirectly be influenced by socio-economic characteristics, we investigated combinations of socio-economic characteristics that gave the highest probability of HWT adoption Since *HWT promotion* alone could only increase the HWT adoption by five percent, compared to situation without promotion activities (Table 2), combinations with other socio-economic factors were tested (Table 3; see also Table S6 for more combinations).

Table 3 showed how different categories in socio-economic characteristics nodes yielded different probabilities of HWT use. Table 3 also showed that, when promotion activities were done in areas with more educated households, the probability of adoption was higher than in areas with lower education (number 1–2). In addition, households who have a piped connection have a higher chance of HWT adoption compared to households that use other types of water sources (number 3–4). Further, even if a household is located in easily accessible parts of rural Nepal, a higher rate of HWT adoption was only possible when such households were able to afford HWT technology and had received promotion activities (numbers 9–10).

Finally, we found that households with a toddler, consisting of educated and relatively wealthy persons, who were aware of and have easy access to HWT products, and with piped water connections are most likely, with 57% likelihood compared to 18% in the baseline, to adopt HWT (Table 3, number 15). Fig. 5 illustrates this causal interpretation and how the value in the all psychosocial nodes being *high* increased compared to the baseline (Fig. 3).

4. Discussion

The presented model illustrates the causal linkages between socio-economic characteristics, psychosocial factors, and adoption of HWT. Furthermore, due to its graphical representation of BBN models, it "facilitates the communication of information to people without

Table 3
Effect of updating socio-economic characteristics on HWT adoption.

No	State for socio-economic characteristics[a]						$P_{use\ HWT}$ = yes (%)
	HWT promotion	Has children under 5 yrs.	Education	Water source	Logistic access	Wealth level	
1	Yes		None				17
2	Yes		College				29
3	Yes			Tap			20
4	Yes			Other			18
5	Yes				Easy		22
6	Yes				Difficult		18
7	Yes					Poor	21
8	Yes					Rich	22
9	Yes				Easy	Rich	29
10	No				Easy	Rich	22
11	Yes	No			Easy	Rich	30
12	Yes	No		Tap	Easy	Rich	34
13	Yes		College	Tap	Easy	Rich	52
14	Yes	No	College	Tap	Easy	Rich	46
15	Yes	Yes	College	Tap	Easy	Rich	57

[a] Empty boxes means that the value of that node did not change or was similar to the baseline condition.

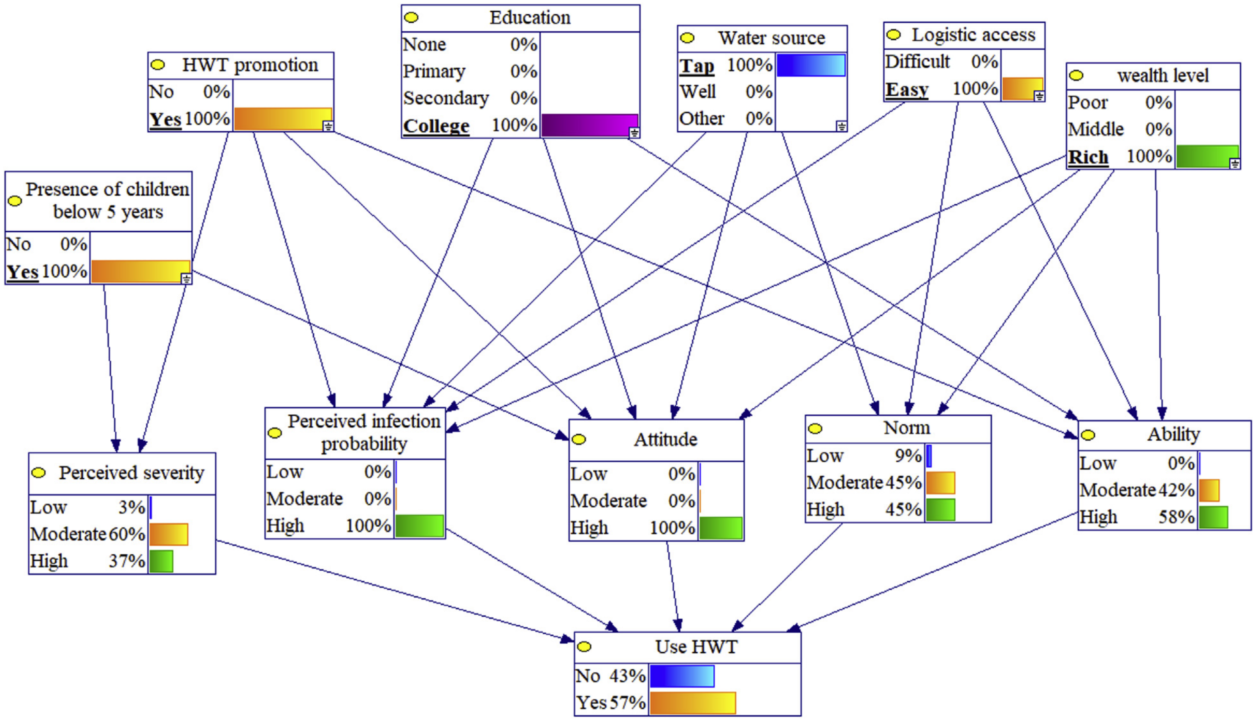

Fig. 5. The best scenario of intervention (i.e., changing *belief*) in socio-economic factors on the outcome node *practicing HWT*.

technical abilities so they can participate better in the decision making process" (Cain, 2001).

The BBNs presented in this paper combined both quantitative and qualitative approaches to facilitate the effective design of interventions in the WASH domain. By analysing the interactions between combinations of variables in a probabilistic manner, the BBN model predicted the likelihood of different scenarios on the adoption of HWT in the study area. However, this has not been done in previous WASH-related *behavioural* studies that mainly used approaches different from BBN, e.g., logistic regression (Altherr et al., 2009; Casanova et al., 2012; Inauen et al., 2013; Stocker and Mosler, 2015).

Our model showed on average a good performance in predicting 83.65% of the output, even though it predicted the correct adoption output being "yes" only 50% of the time. One possible reason is that the ratio between *adopters* and *non-adopters* is quite high (1:3.5), which might make the model "more familiar" with *non-adopters*. Death et al. (2015) suggested using AUC to evaluate the model's performance in this unbalanced situation. Our AUC was 0.85 (STD = 0.005) which suggests good model performance (Greiner et al., 2000).

The maximum predicted probability of practicing HWT by updating the belief in socio-economic characteristics layer was 57%. This is because the parent nodes (i.e., socio-economic characteristics) of each psychosocial factor could not fully explain the observed level of the psychosocial factors. This means that there are probably more socio-economic characteristics that also could influence or explain the levels of the psychosocial factors besides those that we have used in our model.

It is not surprising to see that *education*, household's *wealth level*, and *receiving HWT promotion* were the most sensitive nodes (Table 2) because other studies have found similar results (e.g., Fotue Totouom et al., 2012; Gamma et al., 2017; George et al., 2016; Nauges and Berg, 2009; Opryszko et al., 2010).

If we look at the effect of updating the belief of *individual* psychosocial factors, *norm* and *ability* (action knowledge) are the most influential psychosocial factors behind the adoption of HWT (Table 2). The probability of HWT adoption greatly increased when these psychosocial factors were high. This finding is consistent with other reports that mention that *norm* is an important factor for sustained positive behaviour related to WASH (Gerwel-Jensen et al., 2015; Inauen et al., 2013; Mosler and Kraemer, 2012) On the other hand, *ability*, which in this case is represented by how-to-perform knowledge, has also been found to be one of the important predictors of regular usage of HWT (Altherr et al., 2009). This was also confirmed in the work of Rogers (2003) on *diffusion of innovations* theory, which stated that individuals should have enough how-to-perform knowledge before they are expected to try the innovations.

Although previous studies have also found specific psychosocial factors responsible for the adoption of HWT, a major result of our study is that the change of one psychosocial factor is not enough to boost the adoption of HWT, i.e., greater than 50% for the specific case of rural Nepal. It suggests that targeting multiple psychosocial factors is necessary to effectively change the behaviour in water treatment.

It is surprising to see that node education have a different effect on various psychosocial nodes. In the case of our study, education positively influenced the HWT adoption not via *perceived infection probability* (i.e., education has negative influence), but via *attitude* and *ability*. Cross-tabulation of the sub-factors separately showed that households with higher education perceived slightly lower *vulnerability* and *factual knowledge*. This perhaps is because of implicit bias that educated households have in believing that they know more than they actually do. This advantage, i.e., to visualize the effect of changes one variable on all related variables at once, is one unique aspect of the BBN model that sets it apart from other approaches, such as logistic regression. We could simulate and learn the pattern of how socio-economic characteristics influence people's perceptions and then drive the behaviour. In other words, socio-economic characteristics enable us to understand the system behind the practice of HWT.

4.1. Implications

Our research revealed that there were critical combinations of certain socio-economic characteristics that facilitated the adoption of HWT through corresponding psychosocial factors (Table 3). These findings can be used for targeting specific groups when designing HWT interventions and prioritizing the transformation of non-adopters to improve, i.e., the households with socio-economic characteristics that correspond to high probability of adopting HWT (Table 3 and Fig. 5). These households might then be categorized as "earlier adopters" (a la *diffusion of innovations theory,* Rogers (2003)) and an implementer can target this group because rapid adoption among them might trigger others households to do so (i.e., 'snowball' effect).

This does not mean that we want to "change" people's characteristics by making them rich or attend college as a way to influence the practice of HWT. However such socio-economic characteristics in the BBN model can be used as proxies to simulate potential interventions. For example, Table 2 shows that the availability of tap water resulted in a higher probability of adoption of HWT, compared to other types of water sources. The results suggest that water supplier agencies are one of the potential promoters of HWT products. They could combine their piped water scheme project with other activities to increase the probability of HWT adoption. For example, (1) designing HWT promotion to target the most educated person in each household (i.e., using nodes HWT promotion and education as a proxies), (2) integrating HWT promotional activities within an antenatal program (represented by having children), (3) establishing a distribution network to ensure easier access to HWT products and information for key target groups (represented by logistic access), and (4) assessing target households' willingness and ability to pay for cleaner water prior to procurement of HWT products. Fig. 5 shows the "ultimate" intervention which addresses all the socio-economic characteristics nodes.

Furthermore, our model showed that the combination of the provision of products plus effective promotion activities were better than the provision of products or promotion alone. Some interventions in other studies gave the HWT products away for free or at a subsidised price because HWT are marginally expensive for some households. This 'income' effect was interpreted by our model through wealth level being "rich" and logistic access being "easy". However, as suggested by a previous study on the use of toilet in Terai area, Nepal, the subsidies have to reach poor households. If a non-subsidised program is chosen, the implementers should think about right strategies for self-financed toilets, e.g., by providing microloans (Gerwel-Jensen et al., 2015).

This study underlines some limitations and remarks for the future work. First, this study did not distinguish between different types of HWT promotion activities that respondents received in the past. Previous longitudinal studies revealed that different types of HWT promotion activities resulted in different levels of HWT adoption (Kraemer and Mosler, 2012; Mosler et al., 2013) which is worth modelling in the next study. Second, we also suggest validating the model in other locations to examine how generalizable the CPTs are, especially CPTs corresponding to psychosocial factors node conditional on socio-economic characteristics, and how they might change across contexts. RANAS suggests that psychosocial factors can have different influence on behaviour depending on the situation or location (Mosler, 2012). Third, due to missing values on certain sub-factors in our datasets, the representative psychosocial factors used in this model may not fully reflect the complete meaning of each RANAS factor. Future studies should incorporate all RANAS factors and see how it can better explain the HWT adoption. Even though we argue that targeting multiple psychosocial factors is still the key to increase the adoption rate of HWT, especially when the adoption rate in that area is very low. Fourth, we did not explore attitudes of households towards different HWT methods because the scope of the study was to explore general attitudes towards HWT practice and not to compare different HWT methods. Further, such an assessment would also not have been reliable because most of the respondents only used boiling as a HWT method. Fifth, future studies should investigate our assumption that socio-economic characteristics indirectly influence the use of HWT via psychosocial factors. Lastly, the data of the HWT use was respondent's self-reported HWT practice, which might have been over-reported and could have been subject to bias.

5. Conclusion

The causal relationship between socio-economic factors, psychosocial factors, and WASH-related behaviour have not been investigated in-depth in previous studies. In this paper, we showed how socio-economic characteristics influence the psychosocial factors of people in rural Nepal and how those psychosocial factors work together in determining households' adoption of HWT, while visualising and quantifying their interactions through a BBN model. The findings presented here highlight the complex system underlying HWT adoption. The most important drivers of HWT adoption among individual socio-economic variables were education, wealth level, and HWT promotion, while social norm, and ability to perform the behaviour were influential psychosocial conditions. The presented method is also helpful in setting priorities in behavioural change interventions in the WASH domain, first by observing the socio-economic characteristics of HWT adopter, and also by assessing the combinations of psychosocial factors that can increase the probability of HWT adoption. The results also suggest that the piped water supply project in LMICs is a potential entry point for the high likelihood of HWT adoption, if it is accompanied by other activities as described in this study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2019.04.005.

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