

Impact of mental models on constructed wetland maintenance in semi-arid India

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Abstract

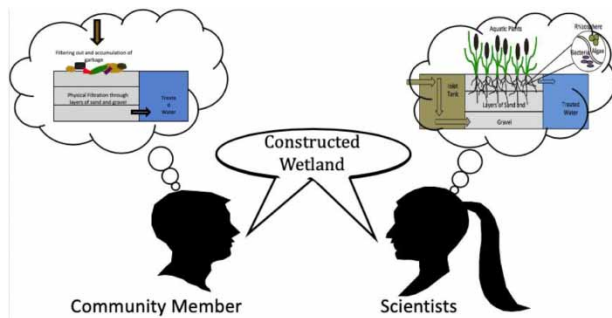
Constructed wetlands (CWs) are a low-cost technology relying on natural processes to treat wastewater and provide a decentralized wastewater treatment option in communities with limited infrastructure. Little is known about their long-term maintenance or monitoring, or the experience of communities who adopt and maintain CWs. This research uses mental models to compare the perspectives of scientists and community members regarding CW maintenance. Forty-three semi-structured interviews with farmers, maintainers, local politicians, CW neighbors, extension agents, and scientists in four villages in south India were conducted. Differences in their mental models reveal the importance of understanding CW ecology, the connection between CW maintenance and treated effluent water quality, and how to monitor and maintain the CW. The results contradict the commonly accepted idea that CWs are a simple technology that is easily maintained. CWs are complex and their complexities need to be factored into decision-making related to choosing what WW treatment is most appropriate in the rural communities for which they are being considered. The study's results highlight the need for radical re-design of CWs so they do not need maintenance or can be maintained intuitively by community members.

Key words: adoption, decentralized wastewater treatment, farmer perception, local knowledge, South Asia

Highlights

- Constructed wetland (CW) may provide a solution to rural wastewater (WW) treatment.
- Maintenance of CW limits nuisances for neighbors and maintains treatment efficiency.
- Mental models (MMs) of experts and community members CW maintenance are compared.
- Gaps in stakeholder MMs reveal potential design barriers.
- CW need to be co-designed with stakeholders to facilitate monitoring and maintenance

Graphical Abstract



INTRODUCTION

Sixty-six percent of Indians live in rural areas (World Bank 2014), away from the wastewater (WW) infrastructure of urban systems, and most WW goes untreated in India (International Institute of Health and Hygiene 2018). The World Health Organization (WHO) attributes a mortality rate of 18.6 deaths per 100,000 people per annum in India to unsafe and inadequate water, sanitation, and hygiene, with a total of 246,088 attributed deaths in 2016 (WHO 2018).

Pilot studies have indicated that constructed – that is, manmade – wetlands (CWs) are a suitable solution for decentralized primary WW treatment in developing countries to improve water quality (Abdel-Halim *et al.* 2008). The wastewater is treated by natural processes associated with the soils, water flow, and vegetation within the wetland, which supports biological, chemical and physical removal of suspended solids, nutrients and pathogen loads. In rural areas, CWs appear to be a better solution than septic tanks and other options currently available (Kumar *et al.* 2016) due to their low cost, use of natural processes, and requirements for minimal maintenance and operation (Tuladhar *et al.* 2008).

Limited research in India and developing countries suggests that treated water quality decreases if CWs are not properly maintained. ICRISAT (2016) reported that if the CW became neglected and regular biomass harvesting did not occur (at least every three months), chemical oxygen demand (COD) removal efficiency decreased by more than half (65 to 30% removal) due to overgrowth of vegetation. In addition, if weeds were not removed, the growth of treatment vegetation was retarded and overtaken (ICRISAT 2016). In a CW in Bhopal, Madhya Pradesh, Starkl *et al.* (2013) identified that treatment efficiency was affected by seasonal overloading of water flow, high evapotranspiration, and clogging.

Less research has been conducted to examine community maintenance of CWs and identify barriers to maintaining decentralized WW treatment units (Mankad & Tapsuwan 2011; Starkl *et al.* 2013). Kumar *et al.* (2016) identified and evaluated six CWs across India that treat community WW. The authors saw that neighbors encountered nuisances including mosquitos, direct contact with WW, and risk of children falling into the CW. In addition, they observed inadequate maintenance with excessive sludge buildup, overgrowth of treatment vegetation, and weed (unwanted plants) proliferation, leading to infrastructure failure (Kumar *et al.* 2016). Starkl *et al.* (2013) examined a CW in Bhopal Madhya Pradesh, India and found that it was not maintained.

CW maintenance is key to improving treated effluent quality effectively but may not happen in rural areas in India. Developing a better understanding of community reaction to CW maintenance may help improve CW technological innovation in India and elsewhere. In this work, the maintenance and monitoring of six CWs in four communities in the semi-arid region of India were studied using a mental model framework. The objectives were to: (i) capture the mental models of CW maintenance

held by different stakeholders (farmers, local politicians, neighbors, and scientists), and (ii) compare those models and identify differences affecting CW maintenance. To meet these objectives, the research questions were: (a) What components of the mental models of the CW socio-ecological system are important for the stakeholders to maintain the CW? (b) How do the CW ecosystem mental models differ by stakeholder? (c) What are the stakeholders' mental models of CW condition monitoring? The aim was to help water engineers and scientists better understand and improve CW design within communities.

Potential of CWs in semi-arid India

Natural wetlands have provided wastewater treatment since societies first produced it. By the 1980s and 1990s, CW technology had disseminated to developing countries in Africa and Asia. A CW is an artificial wetland designed to facilitate the physical and biochemical processes found in natural wetlands to improve water quality. CWs have the potential to reduce pathogens and nutrient loads in WW released to the environment (Kadlec & Wallace 2009).

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Telangana, India, conducted a number of pilot studies on-campus that indicated both that climate conditions there are suitable for CWs and that CWs reduce pathogen and nutrient loads effectively, making the treated water suitable for agricultural irrigation (Kaushal *et al.* 2016; Tilak *et al.* 2016, 2017).

Kaushal *et al.* (2016) found fecal coliform reduction between 64 and 81% in CW effluent over a four-month study. Tilak *et al.* (2017) found that CW total suspended solids (TSS) removal efficiency was 63 to 68%, COD 39 to 45%, and total fecal coliform 53 to 80% over a nine-month period. Over 14 months, NH₄-N removal efficiency was 26 to 32%, NO₃-N 36 to 30%, and soluble reactive phosphorus 20 to 45%. The major mechanism for TSS was found to be physical (Tilak *et al.* 2016, 2017). Aerobic and anaerobic biological removal mechanisms were found to facilitate biochemical oxygen demand (BOD) and COD. *Typha latifolia* was found to uptake 31.5 g-N/kg and 3.9 g-P/kg over the 14-month study. *Canna indica* uptake was 8 g-N/kg and 1.84 g-P/kg for nutrient tissue concentrations over 3-months (Tilak *et al.* 2017). Pilot studies indicated that yields of irrigated chili, eggplant, ridge gourd, and cluster bean decreased respectively with untreated WW, treated WW, and freshwater, suggesting potential beneficial nutrient loading from the WW (ICRISAT 2016).

Inherent clogging of CWs

Subsurface flow through CWs will naturally clog them because some dissolved solids can convert to suspended solids, filling the pores (Kadlec & Wallace 2009), clogging leads to preferential water flow and decreases treatment efficiency. Severe clogging will result in the costly removal, and cleaning and/or replacement of the bed material (De Matos *et al.* 2018). Proper maintenance can reduce clogging and increase CW life (Reddy *et al.* 2014).

Barriers to CW maintenance

In Nepal, one barrier to maintaining CW efficiency is that people perceive them as requiring no maintenance (Tuladhar *et al.* 2008). Kumar *et al.* (2016) identified four types of failure in horizontal subsurface flow CWs in India: poor maintenance, lack of finance, social challenges, and mixed industrial effluents. Social challenges were defined as lack of access by all community members to harvested biomass, lack of ownership by the community of the CW, and lack of an effective institutional mechanism to charge users fees and generate maintenance funds (Kumar *et al.* 2016), but did not explore the underlying causes of poor maintenance. Starkl *et al.* (2015) explored the concept of CW use to treat WW for agricultural irrigation in the Musi watershed, Hyderabad. Their results

indicate that farmers are willing to adopt CWs for irrigation but expect government to pay for their construction (Starkl *et al.* 2015). Willingness to maintain the CWs was not explored.

Theory

Mental models are individuals' perceived understandings of how the world functions, and develop through cultural norms and experiences. Therefore, individuals from the same subcultural group share culturally held mental models. The concept of mental models developed in psychology (Johnson-Laird 1983) and cognitive anthropology (D'Andrade 1995). The fields of natural resource management (Abel *et al.* 1998; Jones *et al.* 2011), environmental psychology (Kearney & Kaplan 1997), and risk communication (Morgan 2002) have adopted the concept of mental models for applied examination of communication, by comparing stakeholder mental models of a phenomenon and identifying differences that could lead to poor communication. Friedrichsen *et al.* (2018) identified four cognitive dissonance mechanisms between stakeholders' mental models that might affect technological innovation: lack of perception of a technology's practicality by the adopter, lack of incorporation of local knowledge into technology development, disagreement of what the local challenges are, and technology that does not solve perceived challenges.

METHODS

CWs in the integrated participatory farmer watershed model

ICRISAT built 28 emergent vegetation, surface flow, and vertical flow subsurface CWs (Vymazal 2010) as part of its Integrated Participatory Farmer Watershed Model. The goal was to provide a clean and stable water source for agricultural irrigation in water-scarce regions of semi-arid India. The CWs are concrete structures with three types of tank – inlet, wetland bed, and outlet – in sequence. The inlet and outlet tanks are open, and the wetland beds consist of alternating layers of sand and gravel with *Typha latifolia* or *Canna indica* planted on the surface. They were designed to suit local WW quality, topography, and land availability with varying numbers of each tank type, and rely on gravity to move the water. Any farmer using the water, however, needs a pump to take water from the outlet tank.

Four research sites were selected on the basis of proximity to ICRISAT, the extensive involvement of CW scientists in problem-solving-related maintenance, and time of establishment. Two communities (2 and 3) had two CWs each (Table 1). In total, six CWs were observed and associated stakeholders interviewed. Due to alteration of the CWs by participants and clogging, neither the extent to which they met international scientific design standards (Kadlec & Wallace 2009) nor current flow patterns (surface vs subsurface vertical flow vs subsurface horizontal flow) could be determined during site visits. Often, CWs in developing countries are either less than perfectly designed (Denny 1997; Kivaisi 2001) or have been altered but continue in use. Two of the CWs had primary treatment: CW 6 had a series of gravel tanks designed for the sedimentation of large organic particles, and CW 5 a large sedimentation pond within the community where the water was retained, and only diverted to the CW for treatment when needed by farmers. Lack of primary treatment before a CW is common in developing countries (Denny 1997).

Three communities (1, 2 and 4) were in Telangana and spoke Telugu, another (3) was in Karnataka and spoke Kannada. The communities, all in the semi-arid region of India, were predominantly Hindu and Muslim.

Table 1 | CW characteristics and the related community

Constructed wetland communities and CWs	Designed capacity (m ³ /d)	Size of village (households)	Unit dimensions (m × m × m)	Year of construction
<i>Community 1</i>				
CW 1	56	500	70 × 5 × 0.9	2015
<i>Community 2</i>				
CW 2	25	125	60 × 3 × 1	2014
CW 3	20	100	20 × 20 × 1	2015
<i>Community 3</i>				
CW 4	50	100–125	N/A	2014
CW 5	N/A	70–80	N/A	2017
<i>Community 4</i>				
CW 6	20	100	N/A	2015

N/A, not available.

Design and sampling

The first author conducted all interviews and site visits during four months based at ICRISAT, and informed consent was obtained from all participants. She had previously collected data at community 1 and observed difficulties related to CW maintenance there. Because it was close by, community 1 was visited eight times in the four months, while the other sites were visited twice. A detailed description of each CW was obtained from the scientist who designed and now oversees the CWs at all four communities, and his interactions with community members observed. Extension agents from a fifth community were also interviewed and photographs inspected while confirming ‘saturation’. Saturation was determined as met when no new concepts, contexts, or maintenance issues arose during new interviews (Bernard 2002).

Purposive sampling was used for the interviews (Bernard 2002). Scientists and extension agents related to the CWs’ development and dissemination were interviewed. Extension agents identified and approached the farmers using the treated WW, neighbors living near the CWs, local politicians, local maintenance individuals, and watershed committee members. Some 43 interviews were conducted: nine farmers using treated WW, one farmer using the harvested biomass, five scientists, 11 extension agents, four neighbor focus groups, six watershed committee members, three local politicians, and four local government sanitation individuals. This purposive sample frame included representation of gender, castes, and religious affiliations to enable understanding of multiple community perspectives (Friedrichsen *et al.* submitted). Interviews were conducted near the CW, in the farmer’s field, in the scientist’s office, in a community space, or in an individual’s home. In communities 1 and 3, the local extension agents translated the interviews personally, while in communities 2 and 4, an extension agent from community 1 with stronger English skills was brought in to translate, and worked with the local agent to identify and approach individuals. Two different extension agents from community 1 helped with translation. The primary translator had collaborated in a previous study (Friedrichsen *et al.* 2018). The second checked a sample of the first translator’s work and translated when the latter was not available. A third extension agent from community 3 translated Kannada. One of the study’s limitations was not having an independent translator, but the extension agents’ connections and rapport with the community were advantageous. Most interviews with scientists and extension agents were conducted in English.

Data collection and analysis

The interview guide was pilot-tested with one extension agent, while three agents provided feedback and direction in developing the interview guide. Semi-structured interviews were used to elicit

participants' mental models indirectly (Bernard 2002; Jones *et al.* 2011) and were audio-recorded (Quinn 2005). Topics in the interviews included: CW function and maintenance, and the CW's effects on the food system. Interviews lasted between 15 minutes and 2 hours, during which time community members were asked to draw the CWs to facilitate discussion. Interviews with neighbors were shorter than those with scientists. Photographs were taken of the CW, the soil, and the crop condition in fields irrigated with the treated WW. Field notes were written at the end of each day of interviews. The first author transcribed the audio recordings, and debriefed and received feedback from the co-authors during data collection.

CW maintenance for WW treatment and use for agricultural irrigation is viewed in this study as a socio-ecological system – that is, a coupled feedback system that includes a natural resource, the ecosystem service it provides, the society, and the management of that resource (Ostrom 2009). The data enabled construction of two influence diagrams (Morgan 2002), representing the mental models of the ecological knowledge related to CW functionality and maintenance among scientists and community members. Two domains –social and ecological – emerged from the data, related to effective CW design, dissemination, and maintenance. This paper explores the ecological knowledge of the stakeholder of the system related to CW maintenance.

RESULTS

Scientists and community members have different mental models of the CW ecological system (Figure 1), and CW functionality (Figures 2 and 3) and the maintenance needed to maintain it. Figure 1 depicts the mental model held by community members of the connections between monitoring the CW's functionality and the roles of physical, chemical and biological treatment mechanisms within it to treat WW. The extension agents' mental model had elements of those of both the scientists and community members. Analysis of scientific publications and interviews with scientists enabled the creation of a single composite drawing of the scientists' perceptions of CW functionality (Figure 2), representing WW entering the inlet tank (left) and moving up through the wetland bed to the outlet tank.

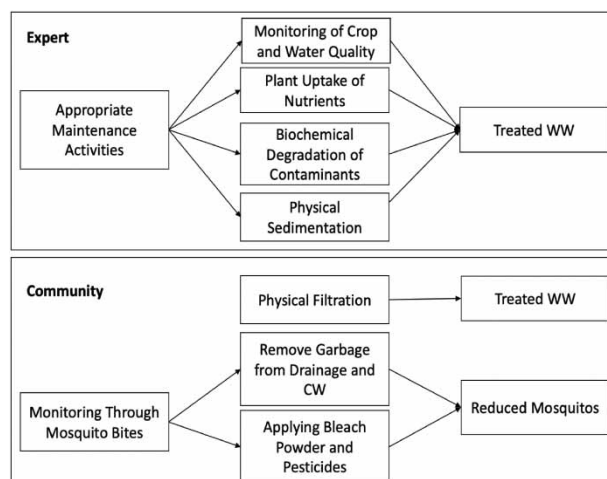


Figure 1 | Expert (above) and Community members' (below) mental models of CW ecology and maintenance.

A single composite drawing of CW functionality as perceived by all community members was also developed (Figure 3). In Figure 3, water enters the top of the wetland bed by gravity, and there are no plants or microbes – providers of the important biological and chemical processes to treat the WW.

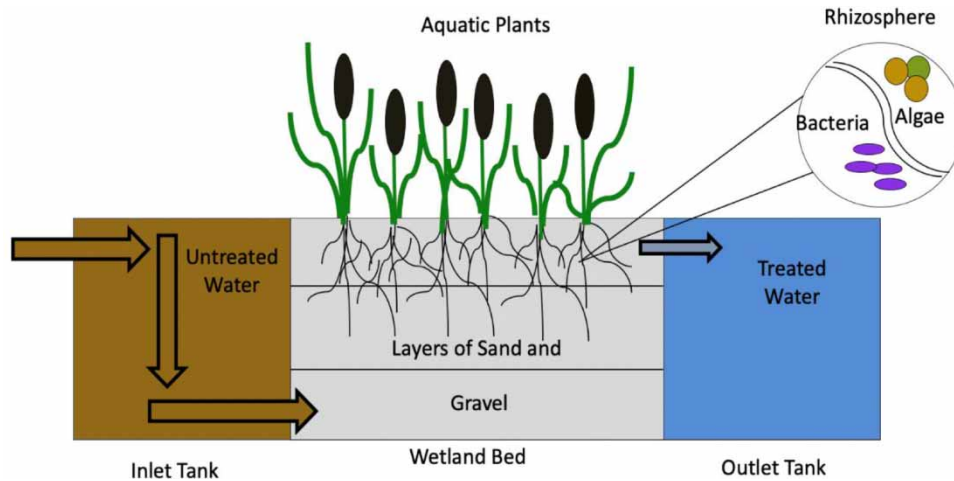


Figure 2 | Scientists' mental model of CW (adapted from ICRISAT 2016).

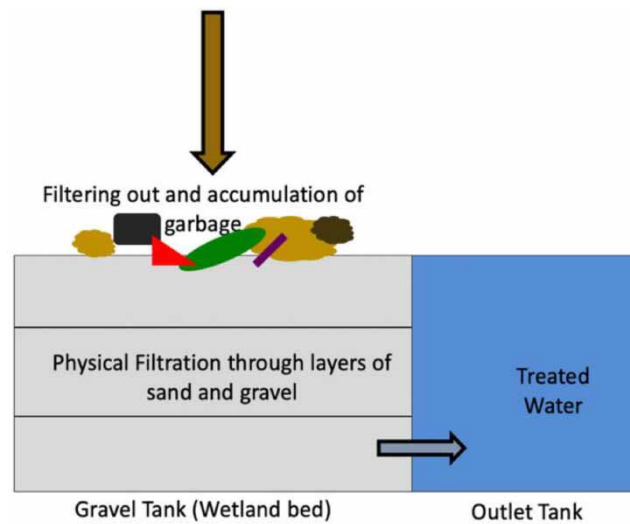


Figure 3 | Community members' mental model of CW.

The wetland bed is labeled as 'gravel tank' in Figure 3 to represent the mental model of the community members who perceive the wetland bed as having the sole function of holding gravel. The results are organized around four misconceptions arising from dissonance between stakeholders' mental models concerning the ecology of CW maintenance – microbial, plant-related, and physical water treatment mechanisms, and CW monitoring and maintenance activities.

Knowledge of CW microbial mechanisms

Community members had no knowledge of the WW treatment microbial mechanisms in the CW, while scientists noted that microbes, which degrade contaminants, are essential to WW's biological treatment in the CW (Figure 1). Community members perceived that adding bleach would sanitize the CW, and reduce the nuisance of mosquitos, flies, and bad odors.

In the community members' mental models, bleach is a purifying agent and useful to improve sanitation. Seven community members mentioned adding bleach to the CW. When asked about side-effects, participant 3 said, 'There is no effect. It is not 100% poison, this is the bleaching powder. We use in the water tanks, bleaching powder. We are using and taking the water, bathing water,

tanks also in households. This is normal, not dangerous. This is safe.’ However, in the scientists’ mental model, bleach affects the CW’s functionality. ‘Bleach powder, actually, this is incompatible with our unit... This is a chemical, which kills bacteria and our (CW) thing is bacterial degradation, even plants. So I see it as something that can harm our project,’ said participant 26. In the scientists’ mental model, adding bleach decreases the CW’s water treatment efficiency by killing beneficial bacteria. Community members have no knowledge of beneficial bacteria and so do not factor them into their mental model. This incongruence in the stakeholders’ mental models shows a communication gap about how the CW functions. If they do not understand the system, community members may think they are improving their water when they are actually harming the CW’s functionality by reducing microbe populations.

Knowledge of CW plant mechanisms

Scientists perceive that plants provide an important part of the water treatment process in CWs. In their mental models, plants extract nutrients from the WW and provide rhizospheres for beneficial microbes that degrade contaminants. Participant 47 said, ‘Whatever impurities are in the wastewater, the plants can utilize and therefore purify and clean the water.’ Scientists’ mental models have plants in the unit that require regular maintenance. ‘So at least monthly once, need to cut the plants, the top-side. So after that cleaning, the water is going, clearly not stagnating,’ said participant 27. Regular maintenance includes applying fertilizer if the WW’s nitrogen content is limited, and removing and composting the plants for use as a beneficial soil amendment (Table 2). Scientists perceive that biomass harvested from the CW is a benefit and resource for the community.

Table 2 | Composite of perceived CW maintenance activities – all stakeholders

Activity	Activity Description
Major	
Repair of the physical structure	Fixing holes or hydrologic problems related to altering the CW structure
Replacing gravel and sand	Remove, clean, and/or replace sand and gravel inside the CW
Pipe cleaning	Removing sludge, etc., from the pipes between the different tanks
Routine	
Backwashing	Pumping water backwards through the unit to remove silt and sludge from the gravel produced naturally by the biochemical treatment process
Weeding	Removal of unwanted plants
Plant maintenance	Fertilizing, cutting, harvesting, and composting plants in the CW for soil amendments
Mosquito management	May include bleach and/or insecticide application, mosquito repellent plants, and/or garbage removal
Drain cleaning	Removing garbage and sludge from drains in the community and those leading to the CW
Garbage removal and awareness	Removing garbage from the CW and spreading awareness in the community that the CW is not a dump site
Bleach application	Application of bleach powder to drains, etc, in or near the CW, to sanitize the water and reduce odors, flies and mosquitos
Algal maintenance	Remove excess algae from the inlet and outlet tanks, and the top of the CW.
Continuous use of treated WW in the storage tank	Consistent constant use of the treated WW so that it does not stand for more than a couple of days
Sludge removal	Remove sludge from the inlet and outlet tanks
Non-Routine	
Fencing maintenance	Installing and repairing holes as necessary
Sand leveling	Leveling the sand and gravel on top of the CW to prevent/inhibit stagnation

Plant-related maintenance is perceived as difficult in the communities. Community members do not feel that they have the tools to cut, remove, transport, and compost the plant biomass effectively. Knowledge of how to build physical structures to make compost is also limited among community members. Thus, most do not perceive compost as a benefit from the CW. One farmer had been given the biomass from the CW but had nothing in which to make compost, so dried yellowing *Cana indica* sat in heaps on the ground. Household garbage and water stagnation in the CWs also prevented plant growth. Site observation revealed either too few plants growing in the CW (CWs 1, 3, and 4) or plants growing out of control (6), dropping their leaves and decomposing inside the CW, and causing stagnation.

Community members have limited knowledge about how plants contribute to CW functionality and many did not include plants in their CW drawings during interview (Figure 3). At site 4, the plants were perceived as a nuisance rather than an essential part of a functioning system and neighbors explained:

'The plants in the constructed wetland are dropping their leaves right now and blocking the constructed wetland... Because of the dropping leaves, there are mosquitos, children are falling sick, and the odor is like hell in the night times. Whenever we tell the sarpanch (village president), field officers, [or] watershed committee they are not taking care of it.' (Participant 15)

In addition to being a nuisance clogging the CW, community members perceived that the plants remove a potential benefit of using treated WW for irrigation: 'When the plants were there, it would not flow. It would not get cleaned...These roots have been multiplying in large quantity. It is just taking all the nutrients away from the water,' said participant 17.

One farmer perceived that the function of plants in the wetland was to help increase WW infiltration. 'The root system of the *Canna indica* plants let the water go into the deeper layer. It acts like sieving activity. The roots of the plants [allow] the water to enter deeper into the soil,' said participant 39.

It is clear from these examples that, in addition to a knowledge gap of plant function in the CW, there is also a misunderstanding about the water's horizontal movement.

Knowledge of CW's physical mechanisms

Participants perceived that the WW should enter via the top of the sand, where the plants are, and come through the gravel at the bottom, instead of entering from the side through the inlet tank (Figure 3). This misconception led them to believe that it is normal to see water and garbage on the CW surface (Figure 3). Failure to understand how the CW's physical mechanisms function can prevent effective monitoring, if people think what they are seeing – garbage, algae, and sludge on top of the sand – are normal parts of the unit's functionality.

Community members mainly perceive that the CW functions like a filter or sieve, with gravity moving water down through the sand, and thus that physical filtration is the CW's only function. They provided detailed drawings of the different layers of sand and gravel within the CW (Figure 3). Since they expect the unit to absorb the impurities in the WW, they expect to need to change the sand and gravel frequently, like changing a filter in a drinking water filtration system. One farmer, participant 32, described building two channels of inlet siltation tanks so that when the sand and gravel become clogged in the first channel 'in three months' it is easy to change to the second channel, and they would only have to change the gravel in the siltation tanks every 6 months.

Similarly, in their mental models, fill material finer than sand, such as soil, would be a more effective filter. One farmer, participant 42, had placed soil on top of the sand in his unit to get cleaner water 'Instead of using sand, I only used this soil because this only gets more purified water'. The soil had slowly infiltrated and clogged the unit until the flow decreased to the point where the

farmer made a hole in the inlet drainage to bypass the CW and use the WW directly. At another site, the state government was building a new road between villages and placed a large pile of soil on top of the CW. It took months for the scientists to convince them that the soil must be removed urgently to stop the unit CW from being clogged.

Knowledge of maintenance and monitoring

Maintenance activities, identified by all stakeholders, are shown in Table 2. The frequencies at which they were thought to be carried out varied considerably, with scientists playing them down to between six months and 5 years, while community members expected between two-weeks and three months. Community members' perception of higher frequency appears to be based mostly on reaction to nuisance occurrence and complaints rather than regular monitoring of the treated effluent quality.

Two community members perceived that decreased water treatment efficiency resulted from reduced maintenance. However, their ability to determine treatment efficiency decreases was limited to monitoring the variables that could be detected by consumption, sight and smell (Table 3). For example, participant 4 said, 'I am also using for fodder, for milking animals, I am drinking that milk, there is no effect.' Participant 32 used visual indicators to monitor changes in water quality with respect to maintenance, saying 'because of the dropping of leaves and some defect in the drainage system there back in the village the water quality has been changed from coconut water to greenish water'. Scientists use biological and chemical variables in water, soil, and crop samples to monitor changes in water quality (Table 3).

In the farmers' mental model, even with observed decreases in water quality, the water was still acceptable for agricultural irrigation. No farmers said that they changed CW effluent use because

Table 3 | Indicators used for CW monitoring and maintenance

Indicator type	Community member	Scientist
Visual	Backflow or flooding Water color Water stagnation Sludge and/or garbage accumulation Treatment plant growth	Treatment plant growth
Biological	Disease prevalence amongst community members and crops Crop productivity	WW BOD Total coliforms Algal species present
Odor	Smell of area around CW Smell of water	
Taste	Rate of spoilage of food grown with WW Taste of milk produced by cows fed with forage grown with WW	
Physical	Mosquito and mosquito bite prevalence Fly prevalence	TSS
Chemical		pH Electrical conductivity (EC) COD Sulfate Phosphate Inorganic nitrogen EC and/or pH of soil irrigated with WW Heavy metal concentration(s) in soil and water
Secondary information	Trust in the institution monitoring the CW	Feedback from stakeholders

of observed water quality changes due to lack of maintenance. They perceived that water moving through or over the CW was sufficient to treat it.

Seven farmers observed, however, that CW effluent water quality was inadequate and stated that the CW needed to be bigger to improve treatment, rather than increasing monitoring and maintenance.

DISCUSSION

It is often claimed in the scientific literature that CWs are a simple technology, with low maintenance requirements and costs (Kadlec & Wallace 2009), and therefore accessible to and appropriate for rural areas in developing countries. This creates a perception by scientists, disseminators, and users that CWs require low maintenance (Tuladhar *et al.* 2008), with the result that less attention is paid to maintenance, making it easy to ignore the CW until a severe nuisance and/or problem develops. This study provides evidence, however, that CWs are not simple to maintain and monitor due to the incongruity between the mental models held by scientists and community members on their functionality. Current CW designs are not intuitive for community members to understand, and require significant communication to develop knowledge of their functionality and monitoring. This is confirmed by Denny (1997), who notes that a CW in Uganda was considered a 'black box' by the local community and that, as long as it existed, it treated WW but removed only 30% of the nitrogen due to limited maintenance.

In this study, participants identified 15 activity types they believe help maintain CWs. Many of these were previously unknown, and are thus not accounted for in CW design and decision-making when determining the most appropriate decentralized wastewater treatment option for a community. Some maintenance activities perceived by community members even harm CW functionality – for example, bleach application.

This study shows how community members adopt and apply pre-existing mental models to understand and maintain CWs. The underlying causes of poor maintenance are examined: misalignment of scientists' and community members' mental models about CW functions and how that affects monitoring and maintenance, and lack of ecological knowledge of WW treatment processes by those maintaining CWs. If scientists want CWs to be effective in the long term, community members' mental models of the ecological functioning of CWs need to be considered in design, training, and installing. Several recommendations are offered.

Design

What if CWs were designed to require little or no maintenance? Could the required maintenance be culturally appropriate? Those designing CWs usually have advanced degrees and are highly knowledgeable in water chemistry, engineering, and soil science. What would a system that requires less maintenance look like? Participant 24, a scientist, said 'natural wetlands don't need to be maintained. Why do these constructed wetlands?' Of course, surface area, depth, water flow, and nutrient concentration are likely quite different between constructed and natural systems, but it is a challenge worth pursuing. What if the CW maintenance requirement in the scientists' mental model was removed? Innovation to solve challenging persistent problems requires radical explorations of alternative solutions (Meynard *et al.* 2017). At the minimum they should be designed so they can be maintained successfully and sustainably by their intended users, thus providing decentralized WW treatment in rural areas.

Assuming that the community will gain the knowledge needed for CW maintenance is not realistic, as it is not their main occupation and they do not generate sufficient income from improved water

quality to pay for maintenance. A human-centered CW design could provide agricultural irrigation, while limiting both plant maintenance and mosquito nuisance, inhibit garbage accumulation within it, and minimize clogging rates. To date, the literature includes no design recommendations for reducing CW monitoring and/or maintenance (Kadlec & Wallace 2009).

Monitoring of ecological functionality

Kadlec & Wallace (2009) collected information needed to operate and maintain, but not monitor, CWs in developed countries. Those maintaining CWs need to be able to monitor themselves. One solution is to develop easy monitoring techniques that require few resources. Existing, low capital, CW monitoring techniques require knowledge, skills and capital that many communities do not have: flow, rainfall, water stage, water temperature, dissolved oxygen, pH, EC, plant cover (Kadlec & Wallace 2009), hydraulic conductivity (De Matos *et al.* 2018), and nitrate and phosphorus concentrations. In this study, community participants identified 15 additional monitoring tools (Table 3) for accessing CW ecological functionality that can be used for front-line monitoring in the absence of laboratory testing. Friedrichsen *et al.* (2018) note that, to continue providing contextually-sensitive soil and water innovations for communities, academic literature and scientists' mental models should accommodate local mental models to ensure successful adoption of innovations by community members.

For individuals worldwide, CWs are complex and misunderstood, and require substantial ecological knowledge to understand, maintain, and monitor appropriately. Massoud *et al.* (2009) propose that the maintenance of decentralized wastewater treatment systems in developing countries could be organized and regulated at a central rather than local level to ensure proper knowledge, and access monitoring and maintenance tools. This would still allow decentralized wastewater treatment systems to provide wastewater treatment without large infrastructural projects but would standardize performance quality. CWs are only one piece in the much larger puzzle of creating a sanitation program in a community.

CONCLUSIONS

Hundreds of millions in developing countries have no access to WW treatment. Water is a limiting resource for agriculture in many countries, and WW is a valuable and available resource. Treating WW to reduce the potential health and environmental risks associated with reuse may improve rural wellbeing. CWs are a low-cost, low-input technology with the potential to provide treated WW for agriculture. CW maintenance is poorly understood by communities, however, which diminishes monitoring and maintenance quality. The results of this study suggest that CW monitoring and maintenance to maintain ecological functionality is complex, and that many rural villagers are not trained or equipped for it. Improving CWs in rural communities will require understanding the differences between the intuitive and observable systems, and the complexity of the technology, to align scientists' and community members' mental models.

Current gaps between mental models of functionality and the role of microbes and plants, and the CW's physical treatment mechanisms, as well as barriers in the community context to CW monitoring and maintenance, may hinder effective communication and, ultimately, appropriate maintenance. If CWs are to be effective in the long term, stakeholders' mental models of the ecological functioning of CWs must be considered when designing and developing monitoring tools. One solution is for CW design to exclude the assumption that communities will maintain them regularly. CWs may be designed to minimize and simplify the monitoring and maintenance activities identified by the participants, to improve functionality after their adoption by communities.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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