Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 43 (2009) 1256–1274

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Four-month Moon and Mars crew water utilization study conducted at the Flashline Mars Arctic Research Station, Devon Island, Nunavut

M. Bamsey[a,*], A. Berinstain[a,b], S. Auclair[c], M. Battler[c], K. Binsted[d], K. Bywaters[e], J. Harris[f], R. Kobrick[g], C. McKay[h]

[a] *University of Guelph, Department of Environmental Biology, 50 Stone Road East, Guelph, Ont., Canada N1G 2W1*
[b] *Canadian Space Agency, Space Science, 6767 route de l'aeroport, Longueuil, Que., Canada J3Y 8Y9*
[c] *University of Western Ontario, Department of Earth Sciences, London, Ont., Canada N6A 5B7*
[d] *University of Hawaii, UH-NASA Astrobiology Institute, Information and Computer Sciences Department, Honolulu, HI 96744, USA*
[e] *California State University San Marcos, 333 S. Twin Oaks Valley Rd., San Marcos, CA 92096, USA*
[f] *Austin Community College, Department of Computer Information Systems, 11928 Stonehollow Dr., Austin, TX 78724, USA*
[g] *University of Colorado at Boulder, Aerospace Engineering Sciences Department, Boulder, CO 80303, USA*
[h] *NASA Ames Research Center, Space Science Division, Moffett Field, CA 94035, USA*

Received 17 May 2008; received in revised form 5 January 2009; accepted 14 January 2009

Abstract

A categorized water usage study was undertaken at the Flashline Mars Arctic Research Station on Devon Island, Nunavut in the High Canadian Arctic. This study was conducted as part of a long duration four-month Mars mission simulation during the summer of 2007. The study determined that the crew of seven averaged 82.07 L/day over the expedition (standard deviation 22.58 L/day). The study also incorporated a Mars Time Study phase which determined that an average of 12.12 L/sol of water was required for each crewmember. Drinking, food preparation, hand/face, oral, dish wash, clothes wash, shower, shaving, cleaning, engineering, science, plant growth and medical water were each individually monitored throughout the detailed study phases. It was determined that implementing the monitoring program itself resulted in an approximate water savings of 1.5 L/day per crewmember. The seven person crew averaged 202 distinct water draws a day (standard deviation 34) with high water use periods focusing around meal times. No statistically significant correlation was established between total water use and EVA or exercise duration. Study results suggest that current crew water utilization estimates for long duration planetary surface stays are more than two times greater than that required.

Keywords: Space analogue studies; Space life support; Water utilization; Moon/Mars exploration

1. Introduction

Even with relatively high level of closure, excluding propellant, water comprises by far the largest consumable mass required on a human space mission. As very few regenerative life support systems have yet been implemented operationally on-orbit for water, better confidence/bounds on crew water use for long duration missions are even more critical, considering only moderate levels of closure may exist for early missions to the Moon and Mars. Past spaceflight experience and ground based studies can provide results useful for future water use estimates (Colombo et al., 1971; NASA, 1970; Verostko et al., 1997; Philistine, 2005; Osburg, 2007). The value of results increases when conducting a monitoring program under operationally relevant mission constraints and in an operationally relevant environment. The decision to conduct the described water study during the 2007 Flashline Mars Arctic Research Station (FMARS) expedition was due to the fact that the expedition was of four-month duration which requires a crew workload that can be sustained for extended periods, such as would be required on a crewed

---

[*] Corresponding author.
E-mail address: mbamsey@uoguelph.ca (M. Bamsey).

0273-1177/$36.00 Crown copyright © 2009 Published by Elsevier Ltd. on behalf of COSPAR. All rights reserved.
doi:10.1016/j.asr.2009.01.009

mission to Mars or the lunar surface. This is in contrast to the operation of current short stay on-orbit missions where crew work loads are on the order of two weeks but are unsustainable over long durations (e.g. Space Shuttle). Additionally, though current on-orbit missions involve maintenance, repair and installation EVAs, they are not being conducted at the high frequency that science will require on a crewed mission to Mars (Hanford, 2006; NASA, 1996). During FMARS2007, regular traverses/EVAs were conducted for the purpose of doing real field science in the FMARS habitat vicinity. The FMARS2007 expedition also included an organized crew exercise program similar to that which may be imposed on future Moon/Mars surface stay crews. Additional study benefits were realized due to the facility size and layout, crew size and the schedule of daily expedition activities. All variables reflected realistic options for future exploration missions. The fact that the crew was operating under communication and isolation constraints very similar to those to be faced by future Mars crews was important but of lesser impact than other factors to the water study itself. Most importantly, this study was unique amongst crew water use studies in that it monitored crew water use in each of its various categories including: drinking, food preparation, hand/face, oral, dish wash, clothes wash, shower, shaving, cleaning, engineering, science, plant growth and medical water. Although required water quality standards may vary between several of the aforementioned forms, this categorized use data provides the life support designer with an improved portrait of probable usage volumes based on quality, waste stream definition as well as crew water utilization requirements in general. Results may also be applicable to water use requirements at remote duty stations, such as those found in the Arctic and Antarctic.

2. The 2007 Flashline Mars Arctic Research Station expedition

A four-month expedition to the FMARS, Devon Island, Nunavut (75 N, 89 W) was conducted during the summer of 2007. Devon Island is the largest uninhabited island in the world and is a well known analogue for the Moon and Mars (Lee and Osinski, 2005; Lim an0064 Douglas, 2003). FMARS was constructed in 2000 and has been used for short duration stays up to one month by crews conducting Mars mission simulations. 2007 was the first time a long duration expedition had been conducted. A crew of seven was selected from a worldwide call of applicants. The final crew composition was an American and Canadian team composed of four scientists and three engineers. Following an engineering visit in late April, the crew arrived on-site on May 1 and resided until final pull-out on August 24. The FMARS facility is a two-story cylindrical structure of approximately eight meter diameter as displayed in Fig. 1.

3. The FMARS water system

At the outset of the expedition, water was produced from melting snow collected in the vicinity of FMARS. Collection involved shoveling snow into large buckets and carrying these buckets into the facility whereby snow was emptied into large metal pots and melted on kerosene heaters. Upon melting the snow would be treated with a small quantity of bleach, and after sufficient settling time carried upstairs and added to the main water reservoir. The transition between melting snow and directly collecting surface water occurred on June 17, 2007. From this date on, water was collected from a stream approximately 300 m north of the habitat. It was collected into small pots and transferred into the same large buckets used for snow collection, then transported by snowmobile-sled or all terrain vehicle-trailer combination back to the habitat where the water would be treated and then transferred by similar means to the main reservoir. Due to unusually warm and dry conditions in the summer of 2007, the creek dried up on July 28, 2007, forcing the crew to travel and collect water from a lake approximately 1.5 km from FMARS. The lake would be used as a source of water for the remainder of the expedition.

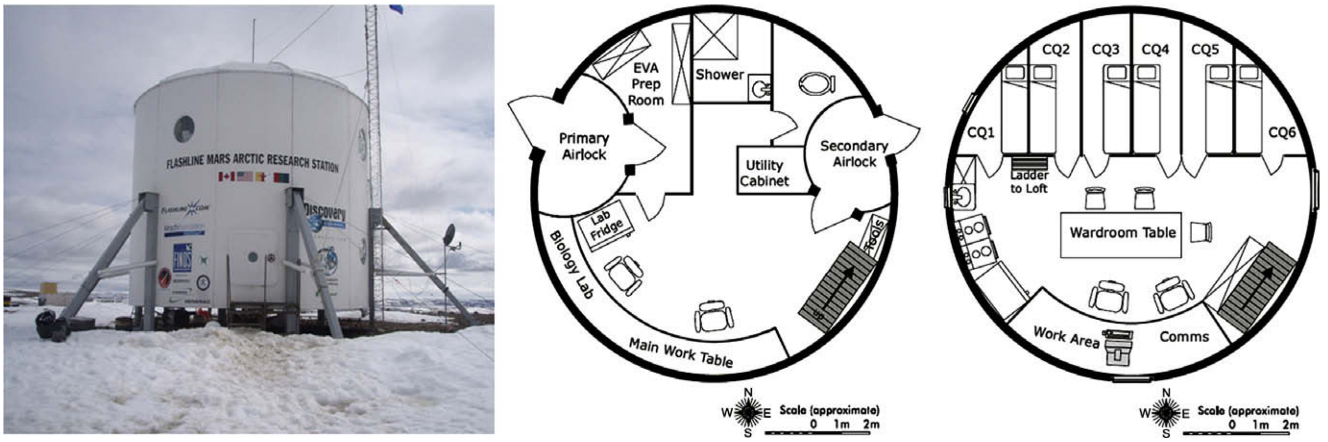

Fig. 1. (Left) Exterior of the Flashline Mars Arctic Research Station, Devon Island, High Canadian Arctic. (Right) Layout of Lower (Left) and Upper (Right) Floors (Osburg, 2004).

The internal components of the FMARS water system include the main 50 gallon water reservoir with approximately 25 gallon fill capacity, a standard water filter with model 5 micron CF1-8 cartridges (Rainfresh), a 12-V pressure pump (SHURflo LLC, Model: Blaster 3901-2214) and a 1500-W water heater (Giant Factories Inc., Model: 115E-1R7N). The habitat piping is of 1/2″ PEX (cross-linked polyethylene) construction. The basic water components housed in the loft area are shown in Fig. 2. Additionally, two combination dehumidifier-water purifier units (Wataire Industries Inc., Model: WII-4010) were used to capture crew condensate for purification and reuse.

It should be noted that water collected from all the aforementioned areas was tested at regular intervals for total coliform and *E. coli*. IDEXX Colilert® water quality test kits were used in conjunction with the lab incubator.

4. Materials and methods

System hardware, water use categorizes examined during the study, the study phases themselves and how data was collected, processed and analyzed are presented in the sections to follow.

4.1. Overview of monitoring system hardware

Six water flow meters were deployed, one on each of the cold and hot lines to each of the water outputs in the habitat including the kitchen sink, bathroom sink and shower (Fig. 3). The chosen sensors are OMEGA FTB4605 as they provide a very large turndown ratio. Table 1 provides basic specifications of these Hall Effect turbine flow meters.

The data acquisition (DAQ) system was composed of a National Instruments Fieldpoint system with one network (Model: FP-2015) and one counter module (Model: FP-CTR-502). Monitoring and data analysis software was correspondingly written in National Instruments LabVIEW 8.0. The actual DAQ system modules and kitchen sink flow meters are shown following installation in Fig. 4.

Fig. 2. FMARS main water reservoir, filter, pressure pump and water heater.

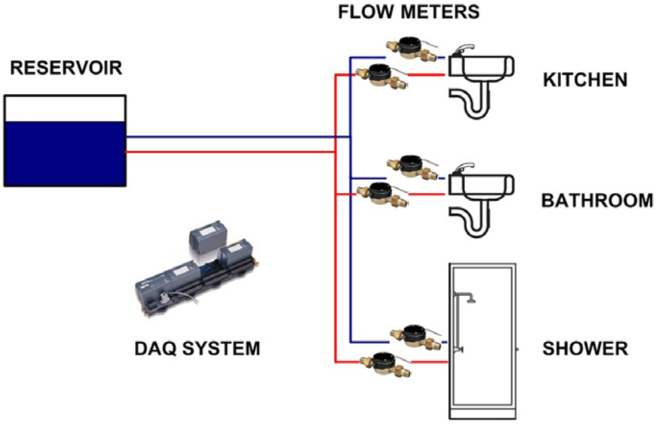

Fig. 3. Basic layout of FMARS sensing system.

Table 1
Relevant OMEGA FTB4605 flow meter specifications.

Parameter	Specification
Flow rate	0.15–13.0 GPM
Accuracy	±1.5% (at 0.66–13.0 GPM) ±2.0% (below 0.66 GPM)
Pulses per gallon	151.4 (pulse = 25 mL)
Input power	6–16 VDC at 10 mA max
Port size	1/2″

4.2. Applied water categorization

The selected water use categories were primarily based upon Hanford (2006) to provide the greatest commonality with current assumptions and baselines. To more easily permit comparisons between this study and others, each category of monitored water use and what it encompasses is described below.

4.2.1. Drinking

Water ingested by the crew directly as water, or the water present in other drinks (juice, powdered milk, tea, coffee, brewed beer, etc.).

4.2.2. Food preparation

Water used in the preparation of food (whether it is ingested or not ingested). For this study, this category does not include the water that is already bound within the food at its place of manufacture. Additional details relating to water used for food preparation are included in a later section on food water.

4.2.3. Hand/Face

Water used to wash the face and hands.

4.2.4. Oral hygiene

Water used for teeth brushing and mouth rinsing.

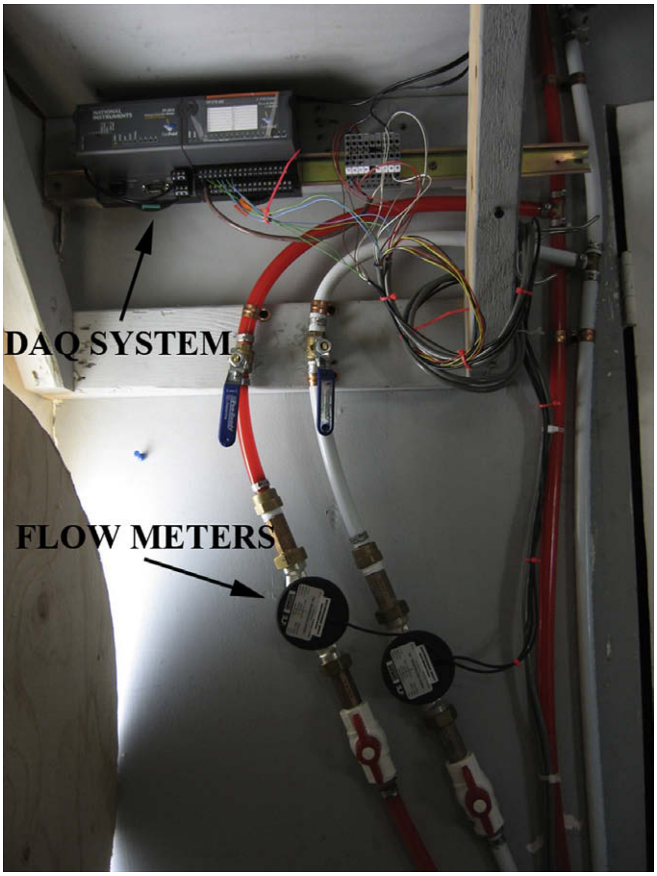

Fig. 4. Image of DAQ system with kitchen sink hot and cold flow meters.

4.2.5. *Dish wash*

Water used to clean dishes and cutlery as well as water used to wash out drinking bottles. The FMARS expedition utilized a standard set of pots, plates, bowls, cups, cutlery and other dishes. As the crew only infrequently prepared food from individually pre-packaged foodstuffs, water used to rinse out the pre-packaged containers, though considered in this category, was a negligible contribution. As dishes were washed by hand during the FMARS expedition this category also includes water used to wash out the dish washbasin.

4.2.6. *Clothes wash*

Water used to wash crew clothes as well as to wash dish towels, bath towels and sleeping materials. No electronic clothes washer was used during FMARS2007. A small hand operated washer (Wonder Wash Corporation, Model: Wonder Clean-Pressure Washing Machine) was used by three crewmembers at the beginning of the expedition while other crewmembers chose to wash their clothes by hand in a washbasin. Following the break down of the washer in mid-June all seven crewmembers used the washbasin.

4.2.7. *Cleaning*

Water to aid in the cleaning of surfaces such as the counters, sinks, and showers as well as other habitat internal hardware and tools.

4.2.8. *Shaving*

Water required by crewmembers to shave.

4.2.9. *Science*

Includes all water related to scientific experiments and their operation. This includes any water used in the treatment of samples as well as the water used to wash scientific equipment such as beakers, tools, etc.

4.2.10. *Engineering*

Water used for any engineering purpose; for example, testing gas lines for leaks, cleaning of engineering tools, cleaning of space suits, water used to flush the water system itself, etc.

4.2.11. *Plant growth*

Water used in one of the two Aerogrow™ systems or for sprouts grown in jars. The Aerogrow™ systems were used to grow salad greens. Each system had a growth area of approximately 700 cm^2 (i.e. $7'' \times 15.5''$). Typically three to four Mason Jar sized or equivalent glass bottles were used to grow sprouts at any given time.

4.2.12. *Medical*

Water use in the cleaning of wounds, sterilizing medical equipment and other water used directly for medical purposes.

4.3. *Categorization considerations*

Though the above categories capture all water use of the FMARS2007 crew they do not encompass all potential water use categories for long duration space missions as other categories may be relevant depending on system architecture. One category important for mass balance is urinal flush water. This was not monitored, as the FMARS facility does not use a water/flush toilet. This in no way limits the study results as urinal flush water is completely system dependent and can simply be added to the water use totals depending on technology selection. Technology dependency can also drive several of the other categories listed above. Science water is likely to be highly variable, as it will depend explicitly on the chosen science program and instrument suite. Despite this variability, science water was monitored over the expedition to provide basic results that can be added to the currently very limited database of estimates. The plant growth category will also be highly dependent on the extent of bioregenerative life support systems utilized on future missions. As early missions will likely not see significant implementations apart from small scale food production systems (e.g. salad machines) the above estimates likely provide an appropriate order of magnitude but can be adjusted depending on final system selection.

4.4. *Study phases*

The FMARS 2007 water utilization study consisted of four main phases:

- Trial phase
- Primary study phase
- Mars Time Study phase
- End of Expedition phase

A description of each study phase is provided in the following text.

4.4.1. *Trial phase*

The trial phase involved a period of 6 days of detailed monitoring between May 26 and May 31, 2007 inclusive. This phase was initially intended to provide an opportunity to trial the sensing system for latter phases. Fortunately, no hardware, software or operational issues arose and thus the collected data is of comparable relevance to the data collected over the other study phases and has been included in the overall water data analysis.

4.4.2. *Primary study phase*

This was an 11-day period of detailed monitoring between June 20 and June 30 inclusive.

4.4.3. *Mars Time Study phase*

Between the period of July 1 and August 7 (inclusive) the crew operated on days with durations equivalent to a Mars solar day, or *sol* (24 h, 39 min, 35 s). This study phase involved a 12 sol period of detailed water monitoring between Sol 1 (July 1) and Sol 12 (July 12–July 13) inclusive.

4.4.4. *End of expedition phase*

This was a 6-day period of detailed monitoring, August 15–August 20 inclusive. Total crew water use was restricted to 70 L/day during this phase, a realistic goal given totals measured in earlier phases. The crew was advised at regular intervals throughout a given day of the total water use up to that particular point. The limit would have been broken for medical or safety reasons; however, this did not prove to be necessary.

Though not categorized, total water use data was collected at all other dates not part of the detailed study periods. That is, for dates not listed above, log sheets were not used but the flow meters and DAQ system were still active. Those dates where only non-categorized water data were collected are referred to as ’non-detailed’.

4.5. *Imposed constraints*

During the development of this study much discussion was had regarding operationally imposed water use constraints. Restrictions on both overall water use by crewmember and by each water use category were discussed in respect to current literature (Hanford 2006; Dussap, 2003; Wieland, 1994; Larson and Pranke, 1999; NASA, 1991). Though challenging due to required data analysis time, it would still have been feasible to be able to notify particular crewmembers of their over and underutilizations each day. Instead, it was decided that no water use constraints would be imposed on the crew (except during the End of Expedition phase). The authors feel this supports a more reasonable study result by ensuring that each crewmember’s level of comfort is maintained, which to a reasonable level will be a requirement for any long duration mission, when maintaining crewmember’s individual and group psychological wellbeing will be of utmost importance. Additionally, the polar environment in which this expedition was conducted imposes by itself an overarching theme of minimizing water use on the crew. Crewmembers understood the time and energy required to collect water and prepare it (e.g. melting snow/ice), and they shared a general intent to minimize the expedition’s environmental footprint. Each crewmember was expected to have different bounds on both total water use and water use in each category, just as future Moon/Mars missions will exhibit differences in utilizations between participating crewmembers. Exploring these bounds by allowing uninhibited use is of high interest. Additionally, as will be demonstrated in this paper, though usage was unrestricted, results will show that the FMARS2007 crew used on average much less water per person than is presently proposed for future long duration Moon/Mars crews.

4.6. *Data flow and software*

The data flow from sensor to final product is depicted in Fig. 5. Three separate LabVIEW software programs were written to handle accumulated data. These are referred to as P1, P2 and P3 in Fig. 5 and a description of each is incorporated into the description of the steps of data flow in the sections to follow.

4.6.1. *Step 1/Program 1*

Logging software was written and embedded on the DAQ controller. This software operated 24 h a day, collecting flow meter pulse data every 2 s. Whenever there was a change in any of the flow meter counter totals, the software program would write to file the date, time and the counter totals for each of the connected flow meters. This software was also designed to write an empty line of data should the controller be restarted, implying a loss of power and thus helping avoid lost sensor data.

4.6.2. *Step 2/Program 2*

As the first of two data analysis programs, this program scans through the initially stored data file and translates flow meter counter information (as nominally the flow meter outputs the number of pulses since its last start up) to actual volume data for each water draw. This alteration is important for the data analysis which follows as it more easily allows the sensor data to be correlated with the log sheet data by the individual conducting the data analysis.

4.6.3. *Step 3/Log Sheet*

The acquisition of categorized water use data (during the Trial, Primary, Mars Time and End of Expedition

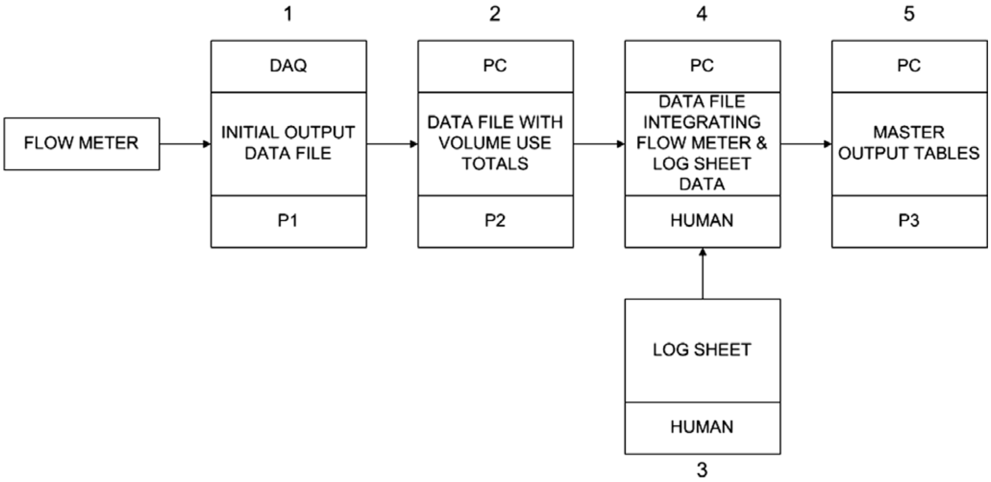

Fig. 5. Monitoring system data flow steps 1–5. *P1* = Program 1, *P2* = Program 2, *P3* = Program 3.

phases) can only be achieved by having the water user classify the water usage. This was accomplished by the placement of a log sheet at each of the habitat water outputs. A sample of the log sheet used in this study is provided in Table 2 below.

Checklists of this sort were placed at the following water output locations: kitchen sink, bathroom, upper level dehumidifier, lower level dehumidifier and near the kettle. The bathroom checklist was used by crewmembers to input data for both the bathroom sink and shower. At each water use, crewmembers were required to input the approximate time of the draw (by using a synchronized watch/clock left by the principal investigator at checklist locations), their initials and a checkmark in the appropriate use category. As flow meter pulse data was collected every 2 s, crewmembers were asked to ensure at least a four second pause between two discrete uses. In reality this did not affect routine operations as by the time the crewmember completes the log sheet, sufficient time has passed for the second user/draw to commence. This log sheet data was then correlated with the electronic data collected by the monitoring system as described in step four.

4.6.4. Step 4/Human

Once full, handwritten checklists were transferred to electronic format (Excel) via manual data entry. Each of the DAQ recorded draws are then correlated with the handwritten data manually by the principal investigator. This combination of the two data streams forms the integrated data file containing the following information: date, start time, end time, cold water use (mL), hot water use (mL), crewmember, location and water usage type. Additionally, four columns called kettle, non-use, power out and notes are included, which record filling the kettle (as opposed to using the water from the kettle), water uses that were not part of nominal operations (e.g. for water monitoring system calibration), water draws that occurred when the power was out (and are thus not recorded by the monitoring system) and finally, any relevant notes pertaining to a specific water draw. Step four is the most time-intensive step as it requires manual matching of the electronic and handwritten data as well as a period of error checking to ensure no erroneous data is entered.

4.6.5. Step 5/Program 3

The final step in generation of the baseline categorized water use data involves a LabVIEW program which takes the integrated data file generated in step four and allows the users to make queries based on date, crewmember and location of water output. The program allows for the selection of multiple dates, crewmembers and location and generates master summary output tables.

5. Study considerations

5.1. Crew statistics

A seven person crew manned FMARS during the four-month expedition. The genders and ages of crewmembers at the time of the expedition are provided in Table 3.

Table 2
Sample crew water utilization log sheet.

Time	CM (initials)	Usage type													Note
		Drinking	Food prep.	Hand/ face	Shower	Oral	Dish wash	Clothes wash	Shaving	Clearing	Science	Engineering	Plant growth	Medical	
8:10 AM	XX			**X**											
8:25 AM	XY		**X**												
Etc.	Etc.														

Table 3
Table of basic FMARS 2007 crew statistics.

Gender	Age
Male	24
Male	26
Male	27
Male	38
Female	26
Female	27
Female	37

5.2. Daily schedule

Because the timing of crew activities influences variance in crew water use over a given day, the basic crew schedule is presented in Table 4. It should be noted that, though this schedule provided a baseline for daily crew activities, it was not explicitly followed in all instances (i.e. if a secondary traverse was conducted in the afternoon, etc.). It is also important to note that each crewmember was free to eat breakfast at a time of their choosing, whereas lunch and dinner were typically eaten together Occasionally, lunches between the habitat crew and the returning traverse crew were staggered.

Another influence on crew water utilization was the assignment of habitat chores. A simple system was devised and followed over the duration of the expedition for assigning these tasks. As there were seven crewmembers and seven primary defined tasks, each crewmember could be assigned a given chore for a given day of the week. This also allowed shower and laundry days to rotate between crewmembers on a daily basis, providing a particular crewmember the chance to shower or wash their own articles of clothing. Table 5 presents the breakdown used for daily crew tasks as well as shower and laundry opportunities.

It should be noted that breakfast preparation was not assigned to a particular individual as crewmembers typically woke at different times and prepared their own individual breakfasts. Also, on Sundays, breakfast and lunch were combined into brunch. Since this meal tended to use rather more dishes than a regular meal, clean-up was shared between two crewmembers.

Table 4
Basic daily crew schedule.

Activity	Time
Wake-up	6:30–7:30 AM
Breakfast	7:00–9:00 AM
Morning meeting	8:00–9:00 AM
Traverse preparation	9:00–9:30 AM
Traverse	9:30–1:30 PM
Habitat tasks (Engineering/Science)	9:30–12:30 PM
Lunch	12:30–2:00 PM
Sample analysis/reporting	2:00–5:00 PM
Report writing	5:00–6:00 PM
Dinner and daily debrief	7:00–8:00 PM
Traverse planning/report writing	8:00–9:00 PM
Mission support window/crew fun	9:00–10:00 PM
Personal time	10:00–11:00 PM
Sleep	11:30 PM

Table 5
Meal preparation, cleaning, shower and laundry schedule (CM = crewmember).

Task	Sun	Mon	Tues	Wed	Thurs	Fri	Sat
Breakfast clean up	N/A	CM2	CM3	CM4	CM5	CM6	CM7
Lunch preparation	CM2	CM3	CM4	CM5	CM6	CM7	CM1
Lunch clean up	CM3/CM1	CM4	CM5	CM6	CM7	CM1	CM2
Dinner preparation	CM4	CM5	CM6	CM7	CM1	CM2	CM3
Dinner clean up	CM5	CM6	CM7	CM1	CM2	CM3	CM4
Upper level clean up	CM6	CM7	CM1	CM2	CM3	CM4	CM5
Lower level clean up	CM7	CM1	CM2	CM3	CM4	CM5	CM6
Shower	CM2	CM3	CM4	CM5	CM6	CM7	CM1
Laundry	CM3	CM4	CM5	CM6	CM7	CM1	CM2

5.3. Non-sensed water usages

Inevitably, there were forms of water use which would not be identified by the monitoring system. Different methods were implemented to ensure these forms of water use were captured. Firstly, though the filling of the kettle would be picked up by the monitoring system the classification of the type of water usage could not be known until the water was actually used for drinking, food preparation, etc. Thus an additional log sheet and measuring cup was included beside the kettle, so that each specific purpose and amount of water taken from the kettle could be recorded. From the data analysis perspective, the DAQ measured water use could then be broken down into its respective categories. Coffeemaker data was handled in a similar manner but was of less complexity as all this water could be considered drinking water – the log was used primarily to determine which crewmember had used the water. Other water that could not be metered included water taken directly from the two combination dehumidifier–water purifier units or large water collection buckets. Similarly, measuring cups and log sheets were placed in their vicinity and used when applicable.

5.4. Power outages

Operating in a remote field camp generally implies the chance of equipment failure or power outages. To handle power outages during which the DAQ system would be non-operational, measuring cups were placed at each system output. During generator oil changes or other activities that required the generator to be offline, crewmembers measured water use using these cups and recorded usage category on the standard checklist. In fact, the study was designed so that it could be conducted entirely in this off nominal state, should it endure for extended periods.

5.5. Crew visits

There were two different phases of the study when there were media visits to the facility. The first visit of one individual occurred between June 1 and June 8. The second brought two individuals and occurred between August 11 and August 14. It should be noted that the detailed study phases were scheduled so that they did not overlap with either of these short visits. Determining per crewmember usages during these non-detailed periods involved multiplying the total daily water use data by a factor reflecting the total number of individuals on-site (e.g. 7/8 during the first visit, 7/9 during the second visit).

5.6. *Food water*

Though water contained in food factors into the water balance of a manned mission, it was not considered in detail during the FMARS2007 expedition. In particular, the exact amount of water contained in the food selected for this expedition was not estimated on a food item by food item basis. Overall, food selection for the expedition was driven primarily by a shelf storage lifetime requirement of at least 1 year. This resulted in the bulk of the food being of dried or canned origin. Though a small amount of canned meat in the form of chicken and turkey was available, the main dinner protein staple was dehydrated textured vegetable protein (TVP). Other staples such as eggs and milk were available in powdered form. Above and beyond the nominal food processing equipment (range, toaster, microwave, etc.) the crew also had access to a breadmaker and a yogurt maker.

Table 6 provides a list of the food prepared for lunch and dinner during the duration of the Primary Study phase. Breakfast, as it was not a meal shared by all crewmembers, is not listed. Breakfasts were primarily composed, according to individual preferences, of porridge, fresh bread, canned fruit and leftovers from the previous day's lunch or dinner.

The most appropriate food system for an early manned Mars mission is not yet defined (Levri et al., 2001). As total crew water use depends on the water contained in food and food preparation water, the results of this study may or may not prove to be completely aligned with future food system values. Nonetheless, it is clear that the data provide a reasonable baseline, especially if food selection is of the mixed variety, including both low moisture content (e.g. dried foods) with more intermediate and normal moisture content foods.

Table 6
List of main meals during the primary study phase.

Date	Lunch /dinner
20-Jun	Chicken noodle soup, bread/TVP burgers, carrots
21-Jun	Sauerkraut, beef jerky, leftovers/Spaghetti, tomato sauce
22-Jun	Scrambled eggs, rice/TVP spaghetti, homemade cheese, carrots
23-Jun	Porridge, bread/Routine, homemade cheese, bread and salami
24-Jun	Waffles, eggs/Chicken curry, couscous
25-Jun	Chicken curry, couscous/Turkey loaf, mashed potatoes, gravy
26-Jun	Omelet, spam/Macaroni and cheese, sprout salad
27 Jun	Macaroni with chicken/Pizza with the leftover macaroni
28-Jun	Macaroni with egg, soup/Egg noodles, chicken TVP, sprouts
29-Jun	Pea soup, macaroni noodles, leftovers/Sprouts, rice, chicken TVP
30-Jun	Macaroni with chicken, canned chili/Quinoa, spinach, chicken TVP

Even with a moderately plausible space based crew diet, it should be noted that estimated water contained in food is only between 0.5 and 1.1 L/CM-day (Philistine, 2005; Bobe et al., 2007; NASA, 1991). Thus study values can be adjusted by their addition if desired.

5.7. *Beer brewing*

The FMARS2007 crew brewed three small batches of beer during the four-month expedition. Each batch was on the order of approximately 24 × 590 mL bottles for a total of approximately 14.2 L each. In regard to how the water used in brewing was handled, it was recorded on the day that it was removed from the water distribution system and not the specific date it was consumed. This form of accounting was preferred because on the date that brewing began, this approximately 14.2 L was removed from the water distribution system and locked up outside the system for several weeks (in contrast with kettle, coffee-maker, etc. use), a non-negligible effect. For the life support designer it is this data that will have a bigger influence on system sizing and other parameters. Though alcohol on manned missions is always a point of debate, and alcohol may or may not be included on initial Mars sorties, it may, in appropriate moderation, provide some benefits from the perspective of crew psychology.

5.8. *Record of other influences*

Several other variables that could potentially influence crew water use were also recorded throughout the expedition or (in some cases) during select study phases. These include: the first and second floor temperature and humidity in the habitat (recorded twice daily), basic traverse information (participants, duration, etc.), crew exercise information, prepared meals, hygiene wipe use and hand sanitizer consumption. Sections to follow give detailed results and the potential relation of several of these factors to crew water use.

6. Data verification

Immediately upon installation and on a weekly basis the functioning and accuracy of the sensing system was checked. In each case, 1 L of water was drawn from each of the hot and cold lines of the kitchen sink, bathroom sink and shower. A pass was granted if the measured data was between 0.975 L and 1.025 L. Values less than 0.975 L or greater than 1.025 L would imply an issue with the flow meter. All system checks conducted during the expedition were in range, and provide confidence in the collected data.

Additionally, 1 week following flow meter installation and at the end of the expedition the sensors where physically removed from the system and thoroughly inspected. In both cases, no issues were apparent e.g. no flow blockages, wiring issues, etc.

7. Results

Total and categorized water use data, including number and timing of crew water draws as well as the influence of several tracked variables on crew water use are presented in the sections to follow.

7.1. Total water use

The water use monitoring program commenced on May 26, 2007 and was completed on August 20, 2007. During this period total daily crew water use was recorded over the course of every day. Although daily summary information is not available for three of the dates within this range due to issues with the water distribution system itself (June 24 and August 10–11), reliable 11), reliable water use data was collected for the remainder of the 86 study days. Daily crew water use totals are presented in Fig. 6. Breaks in the plot denote the aforementioned three study days where total water data was not available.

While the average total crew daily water use was 82.07 L over the expedition, Fig. 6 also demonstrates that there is considerable variation in total water use between expedition days (standard deviation of 22.58 L). This in itself is an important result as it represents that average daily water use is only one aspect of the crew water use story and that references presenting solely a per crewmember average do not provide sufficient information for full water system design. Estimated minimum and maximum water use values are equally important. Though daily averages are not sufficient individually, they do provide a point of comparison for differences in the various study phases and the influence of the monitoring system itself on crew water use, Table 7.

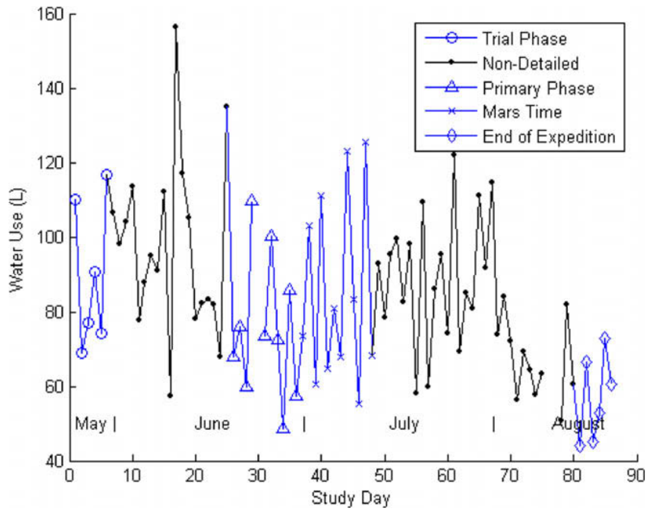

Fig. 6. Total daily crew water use by study phase from May 26 to August 20 inclusive.

Table 7
Total daily crew water use and per crewmember averages by study phase (*Note.* Earth Time Study phase A does not include the End of Expedition phase while B does include the End of Expedition phase).

Dates/study phase	Daily Avg. (L)	Per CM (L)	Per CM Std Dev (L)
Trial phase	89.55	12.79	2.82
Primary phase	75.13	10.73	2.71
Mars Time phase	84.82	12.12	3.52
End of Expedition phase	56.98	8.14	1.67
Earth Time Study phases A	88.53	11.50	2.85
Earth Time Study phases B	74.11	10.59	2.97
Earth Time non-detailed	91.81	13.12	3.67
Mars Time non-detailed	84.97	12.14	2.57
All Study phases	77.89	11.13	3.21
All non-detailed	88.32	12.62	3.15
All dates	82.07	11.72	3.23

Table 7 shows that average per crewmember usage rates throughout the expedition were approximately 12 L/day. Considerable variation exists in measured water use between the various study phases and detailed versus non-detailed monitoring phases. Some initial conclusions can be drawn from the above data. Firstly, though the Mars Time Study phase showed a higher per crewmember usage rate of 12.12 L/sol compared with the Earth Time Study phases at 11.50 L/day (without End of Expedition phase included), the data from the non-detailed dates is opposite in that the Earth Time days used more. Results above also demonstrate that crewmembers used approximately 1.5 L/day less during the detailed study phases than in the non-detailed periods (when categorized water information was not being collected).

7.2. Categorized water use

Few studies have attempted to quantify the various categories of crew water for long duration space missions. Of those which have, only the main water use categories are considered. To the best knowledge of the authors this study is the first to quantify each specific form of water use for crewed missions through direct measurement. Current Moon/Mars crew water use estimates are almost entirely based on a sole source (NASA, 1991). Values in this reference were used as design parameters for the International Space Station (ISS) environmental control and life support system. Very little work in recent years has been conducted to validate these design parameters using new, potentially more operationally relevant environments for Moon/Mars surface stays. Now operational, the ISS is one potential venue for such a study, but it hosts no sensors for water use tracking, apart from condensate monitoring (Philistine, 2003). Actual ISS usage rates are estimated based on the number of potable and technical contingency water containers used over given periods, but provide little information on the purpose of the water use (Philistine, 2003). The most inclusive categorized water use results as of late are those collected during the Lunar-Mars Life Support Test Project (LMLSTP) (Verostko et al., 1997). The deployment of a suite of flow meters allowed for categorized water use measurements to be taken during the FMARS2007 expedition. These results are presented for the crew of seven over various study phases in Tables 8–11.

The categorized water data can help answer some of the questions regarding day-to-day total water variance. The first observation, when comparing standard deviations of the various uses, is that dish wash and clothes wash vary the most between days. In fact, clothes wash water has a standard deviation of more than 17 L during the Primary and Mars Time Study phases. Though the crew had a fixed clothes wash schedule (Table 5), this schedule was deviated from frequently, due to other crew commitments e.g. a more aggressive traverse schedule, lab analyses, habitat maintenance, etc. This could result in days when crewmembers were not able to do their laundry, so that multiple loads of laundry were required the following day. Additionally, there was some variance in the water required by each crewmember for this task. Though not as significant, the same issues arose with shower water use. Drinking water also shows a moderate amount of variation. The variance in drinking water primarily stems from the fact that crewmembers each possess one litre drinking bottles which may be filled the day prior to the water's actual consumption. There were also large drinking water uses on beer brewing days (e.g. sol 2). Dish wash water use variance was primarily a result of specific meal size and food selection, as well as the individual who was tasked with the dish washing duty, as some crewmembers typically used more water than others for this purpose. If large variations due to the largest contributors (i.e. clothes wash and dish wash) are determined to be undesirable, more consistent water use could be achieved through the use of a clothes washer and a dish washer. This would help eliminate the variation based on different crewmember water requirements for these particular activities, but would likely not help avoid schedule constraints pushing these tasks to a later day. Even with the potential for crew time savings that washing machines may provide, it is not clear whether they would increase or decrease crew water use.

Collected categorized data also allows basic insight into male versus female crewmember water use. It should be noted that due to the relatively small crew numbers that it would not be prudent to extrapolate these results universally. It was found during FMARS2007 that, on average, male crewmembers used approximately 85.4% of the water that an average female crewmember used. The largest variations are due to female crewmembers using more in the clothes wash (∼700 mL/day), shower (∼350 mL/day), dish wash (∼350 mL/day), oral (∼350 mL/day), plant growth (∼200 mL/day), and science (∼200 mL/day) categories whereas male crewmembers used more hand/face (∼300 mL/day) water. As stated, it is important to realize that these values do not necessarily reflect a just comparison between male and female water utilization as the results were also highly a function of the roles taken on by specific crewmembers. For instance a female crewmember was charged with tending to plant growth and all three of the female crewmembers were scientists while only one male crewmember was a scientist. When not including these more role specific categories (science, plant growth, engineering, medical), male crewmembers used approximately 88.6% of the water that an average female crewmember used. Additionally, the standard deviation of water use between male crewmembers was 740 mL/day, while that for female crewmembers was 4344 mL/day, which demonstrates that the variation in water use between gender was likely more heavily a result of certain crewmembers rather than gender.

Upon investigation, it is evident from Tables 8 to 11 that the daily totals do not perfectly equate with the total daily crew water use in Fig. 6. This is a result of human error, in that on occasion, crewmembers would forget to mark the log sheet when drawing water from the system. It is assumed that it is equally probable that any one of the various water use categories could be forgotten, thus the values presented in the categorized water use summary tables can be scaled up to reflect the missed data. The percent differences between the monitoring system logged data and the log sheet logged data are given in Table 12.

As can be seen, the Trial phase shows the largest discrepancy between the system logged and manually logged water use. This is somewhat predictable, as this is the phase when crewmembers were becoming accustomed to filling out the log sheets. The overall omission rate is quite low: in all of the Primary, Mars Time and End of Expedition phases, less than a five percent difference exists. Several methods are proposed in later sections to reduce these differences in future studies.

7.3. Crew water draws

The study monitored the number of water draws (i.e. each time a faucet was opened) as this information could prove useful to future life support system designers. The results are provided in Table 13 and demonstrate that the approximate average number of water calls per day per crewmember are 28.9 total draws and 14.6 unique draws. Total draws include each specific time the water outlets were open and then closed while unique draws represent each particular water use activity (e.g. a crewmember may open and close the faucet 10 times during the course of dish washing).

The variance of water calls and volumetric use over a particular day is also of importance. The collected data allows for an analysis of both these parameters. An average of unique water calls per day plotted by hour over all study phases is presented in Fig. 7. The number of calls variable is a sum of all uses including the kitchen sink, bathroom sink, shower, water purifier and bucket. As is apparent

Table 8
Trial phase categorized water use summary.

Date	Total per usage type (mL)													Daily total (mL)
	Drinking	Food prep.	Hand/ face	Shower	Oral	Dish wash	Clothes wash	Shaving	Cleaning	Science	Engineering	Plant growth	Medical	
26-May	17575	9700	4375	17100	1775	29125	16800	0	100	1075	775	0	0	98400
27-May	12625	3200	4350	0	4525	28050	0	0	150	0	0	0	0	52900
28-May	13400	11375	3900	12775	2600	22325	5750	0	175	2000	0	0	0	74300
29-May	19100	5600	6500	9225	5300	34825	5575	0	0	0	0	500	0	86625
30-May	18300	5800	3850	7475	3625	27500	0	0	200	0	450	2000	0	69200
31-May	16350	7475	2975	10250	4050	32750	24675	0	625	0	0	0	0	99150
Avg	16225	7192	4325	9471	3643	29096	8800	0	208	513	204	417	0	80096
Std Dev	2659	2976	1180	5718	1286	4374	9906	0	216	846	333	801	0	18070
CM Avg	2318	1027	618	1353	521	4157	1257	0	30	73	29	60	0	11442
Std Dev	380	425	169	817	184	625	1415	0	31	121	43	114	0	2581

Table 9
Primary Study phase categorized water use summary.

Date	Total per usage type (mL)													Daily total (mL)
	Drinking	Food prep.	Hand/face	Shower	Oral	Dish wash	Clothes wash	Shaving	Cleaning	Science	Engineering	Plant growth	Medical	
20-Jun	15600	13375	4575	10675	2700	19700	0	0	50	800	0	0	0	67475
21-Jun	16675	6325	3000	11325	2925	20000	12000	975	1050	0	0	0	0	74275
22-Jun	18525	7475	4500	5925	3950	14775	400	2025	0	0	0	0	0	57575
23-Jun	24775	6625	2250	0	2250	22250	50100	0	0	0	0	425	0	108675
24-Jun	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
25-Jun	13400	3100	6050	425	2825	22600	19050	950	0	0	450	0	0	68850
26-Jun	18000	5300	6975	0	900	29375	35900	0	50	0	0	825	0	97325
27-Jun	16875	9200	2700	9600	3025	15725	13100	0	100	0	0	200	0	70525
2S-Jun	12175	4125	3575	10100	2475	14700	0	25	50	0	0	375	0	47600
29-Jun	15800	5275	3225	4400	3075	21000	23925	750	0	0	0	6025	0	83475
30-Jun	23950	4150	4575	3000	1825	14650	0	250	0	0	0	350	0	52750
Avg	17578	6495	4143	5545	2595	19478	15448	498	130	80	45	820	0	72853
Std Dev	4062	3004	1502	4625	818	4718	17204	675	325	253	142	1848	0	19214
CM Avg	2511	928	592	792	371	2783	2207	71	19	11	6	117	0	10408
Std Dev	580	429	215	661	117	674	2458	96	46	36	20	264	0	2745

Table 10
Mars Time Study phase categorized water use summary.

Date	Total per usage type (mL)													Daily total (mL)
	Drinking	Food prep.	Hand/face	Shower	Oral	Dish Wash	Clothes wash	Shaving	Cleaning	Science	Engineering	Plant growth	Medical	
Sol1	12675	5900	6075	425	2575	31050	11525	0	1250	*0*	0	0	0	71475
Sol2	31775	2675	5225	15800	3650	33075	7200	0	675	0	0	700	0	100775
Sol3	15525	3900	3625	3025	3400	29975	0	0	0	0	0	400	0	59850
Sol4	18075	3575	4075	9575	1875	14925	38625	0	0	0	0	1375	0	92100
Sol5	21425	5250	6050	5850	1800	19975	0	450	0	0	0	500	0	61300
S0I6	17S00	6775	6375	7900	3475	19S75	16100	725	0	0	1075	275	0	80375
Sol7	14700	3850	4700	2525	2525	20550	14450	450	0	0	0	750	0	64500
Sol8	23750	5500	5800	2175	2500	59950	13450	0	6375	0	0	800	0	120300
Sol9	20850	8250	7225	9425	3875	21300	10000	0	250	0	0	1300	0	82475
Sol10	16S50	5300	4125	3075	2900	14900	0	0	0	5425	0	550	0	52925
Sol11	15275	5375	4000	7825	4525	24400	58300	0	0	0	0	1100	200	121000
Sol12	20375	2075	6350	5175	4375	28300	0	100	25	0	0	1400	0	68175
Aug	19073	4869	5302	6065	3123	26523	14138	144	715	452	90	763	17	81271
Std Dev	5127	1742	1172	4299	904	12136	17648	251	1824	1566	310	453	58	229S5
CM Avg	2725	696	757	866	446	3789	2020	21	102	65	13	109	2	11610
Std Dev	732	249	167	614	129	1734	2521	36	261	224	44	65	8	3284

Table 11
End of Expedition phase categorized water use summary.

Date	Total per usage type (mL)													Daily total (mL)
	Drinking	Food prep.	Hand/face	Shower	Oral	Dish wash	Clothes wash	Shaving	Cleaning	Science	Engineering	Plant growth	Medical	
15-Aug	15400	S75	1675	0	1975	10775	0	0	0	9275	0	300	0	40275
16-Aug	15625	8575	2700	4650	2500	21575	0	1150	0	7325	0	0	0	64100
17-Aug	18875	4200	4300	2825	3175	10600	175	0	75	1250	0	0	0	45475
18-Aug	16450	3700	3350	2200	2325	15650	5925	0	0	0	0	0	0	49600
19-Aug	21100	5625	5700	3500	2075	28500	0	0	125	1500	0	0	0	68125
20-Aug	18150	3200	3925	11125	2775	19075	0	0	125	0	75	0	0	58450
Avg	17600	4363	3608	4050	2471	17696	1017	192	54	3225	13	50	0	54338
Std Dev	2202	2581	1384	3796	450	6872	2406	469	62	4027	31	122	0	10964
CM Avg	2514	623	515	579	353	2528	145	27	8	461	2	7	0	7763
Std Dev	315	369	198	542	64	982	344	67	9	575	4	17	0	1566

Table 12
DAQ System Logged vs. Log Sheet Water Use Data ('DAQ System Log' includes all flow meter sensed data as well as recorded dehumidifier, non-power or bucket use data, 'Log Sheet' data includes all data accounted for on log sheets i.e. categorized water data).

Study phase	DAQ Log (L)	Log sheet (L)	% Difference
Trial phase	537.27	480.58	−10.6
Primary phase	823.20	792.70	−3.7
Mars Time phase	1018.70	975.25	−4.3
End of Expedition phase	341.88	325.80	−4.7

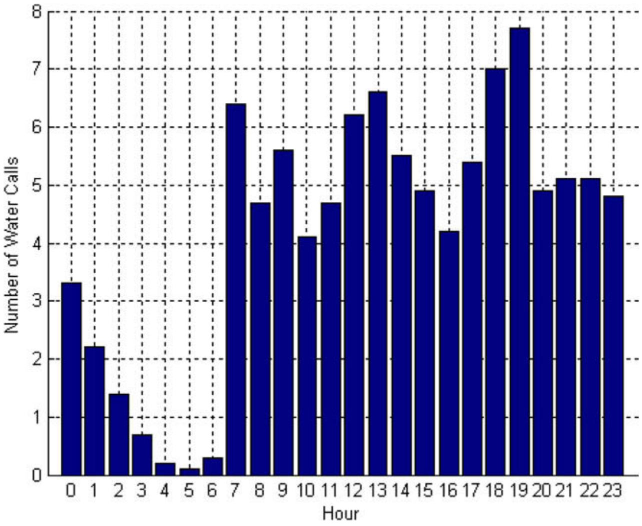

Fig. 7. Per day – hourly water calls averaged over all study phases (0 = 12:00 midnight to 1:00 AM; 1 = 1:00 AM to 2:00 AM, etc.).

from this plot, the number of water calls declines significantly during crew sleep period, with an average of less than one crew water call per hour between 3:00 and 7:00 AM. Additionally, as would be expected, the number of water calls increases before, during and following meal times. This increase is a result of food preparation and increased crew activity in the kitchen area.

More telling is the hourly variance of total crew water use over a given expedition day. Results are first presented in tabular format per specific study phase in Table 14, following which the overall average over all study phases is presented in graphical form in Fig. 8. Table 14 shows that all study phases follow the same general water use variation over a given day. It is important to note that the total daily use values presented in Table 14 do not correlate one to one with those presented in Table 7, this is due to the fact that kettle, bucket and dehumidifier water are not included in the results of Table 14.

Fig. 8 shows that total crew water use averages less than 1 L/h between 12:00 AM and 7:00 AM. Additionally, peak average hourly usage rates are typically in the vicinity of 7 L/h.

The hourly water use data presented provides useful input to the life support designer, helping better define nominal buffer and stowage requirements of a Mars or Moon surface crew. Depending on the recycling system settling time, the above data provides a baseline for total crew water required. In the most simplistic example, with 100% system closure in the water system and a 2-h recycling settling time, the spacecraft would only require approximately 14 L of total system water for a crew of seven (defined by the high use periods surrounding dinner). This simplistic example does not consider off-nominal circumstances and only considers average water use (different days will require more water than others), but represents the basic methodology of how these values could be incorporated into system design.

7.4. *Other study variables*

To facilitate the comparison of this study with others, several variables that may influence water use were tracked and the results are provided in the sections to follow. Additionally, these sections contain analysis results of several specific water usage types or variables.

7.4.1. *Hygiene wipes*

During the Primary Study phase the crew monitored the number of disposable hygiene wipes used. Each crewmember was provided a checklist and additional checklists were posted in the toilet room, bathroom and science lab. The hygiene wipes were of the unscented Teddy's Choice® quilted baby wipes variety and measured 17.3 × 19.1 cm. The usage totals and location of use data are provided in Table 15.

Table 13
Number of water draws per day for each study phase ('Non-DAQ' draws include dehumidifier, non-power or bucket uses, 'Total' includes all draws while 'Unique' conflates all draws that are for one particular action e.g. dish washing may require that the faucet is turned on and off multiple times though the same activity is being conducted throughout).

Study phase	Number of water draws per day							
	Kitchen	Bathroom	Shower	Non-DAQ	Total	Std Dev	Unique	Std Dev
Trial phase	149	56	6	5	217	19	102	10
Primary phase	130	53	8	4	196	30	102	7
Mars Time phase	138	60	8	5	210	41	106	14
End of Expedition phase	126	48	5	1	180	24	97	12
Avg Earth Time Study phases	134	53	7	4	197	28	100	9
Avg All Study phases	136	55	7	4	202	34	102	12

Table 14
Per day – hourly total crew water use by study phase.

Hour	Water use by study phase (L)					
	Trial	Primary	Mars Time	End Exp.	All	All Std Dev
0	0.45	0.61	0.52	0.83	0.59	0.62
1	0.37	0.76	0.28	0.40	0.46	0.63
2	0.35	0.30	0.28	0.50	0.34	0.68
3	0.00	0.31	0.13	0.31	0.19	0.47
4	0.00	0.01	0.01	0.00	0.01	0.02
5	0.00	0.00	0.04	0.00	0.01	0.05
6	0.03	0.00	0.06	0.08	0.04	0.11
7	3.36	2.34	3.22	1.15	2.62	1.85
8	4.16	1.58	1.62	0.45	1.85	2.56
9	5.54	1.29	5.52	2.96	3.83	4.76
10	1.30	1.93	2.60	1.32	1.95	1.91
11	2.64	4.27	2.25	2.93	3.03	3.20
12	3.03	2.61	4.89	3.66	3.67	3.34
13	6.00	7.55	7.36	4.43	6.66	10.74
14	4.54	3.27	5.50	3.94	4.40	5.51
15	3.97	1.43	4.79	1.12	3.01	3.77
16	3.30	2.45	2.82	1.45	2.56	3.03
17	8.98	3.68	6.43	3.47	5.55	7.15
18	8.91	5.88	8.09	4.07	6.87	6.50
19	8.55	5.58	7.48	7.05	7.03	6.43
20	6.05	9.39	6.02	4.39	6.73	8.22
21	5.61	12.49	3.02	2.44	6.16	11.08
22	0.62	3.41	3.19	2.45	2.67	3.29
23	2.34	1.76	3.65	4.94	3.09	3.72
MT Extra	N/A	N/A	1.53	N/A	1.53	3.07
Total (L)	80.10	72.85	81.27	54.34	73.29	21.00

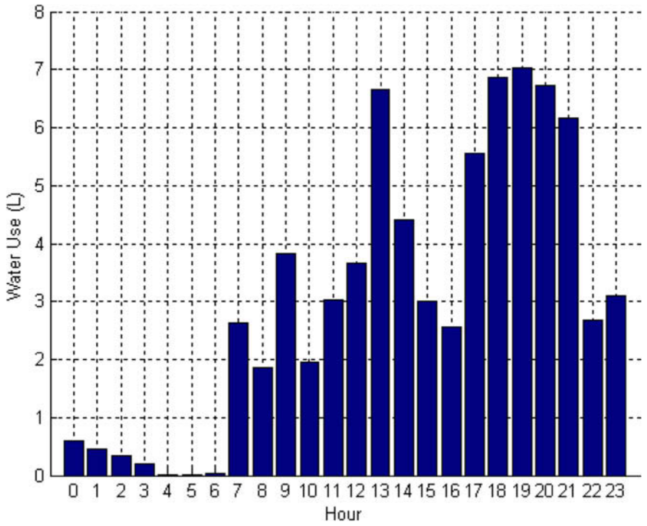

Fig. 8. Per day – hourly total crew water use averaged over all study phases.

For comparison, ISS crewmembers use wet hygiene wipes (of similar size) at a rate of 4.7 per day average per crewmember (Hanford, 2006). ISS crewmembers also average approximately three dry hygiene wipes (29.2 cm × 30.5 cm) and several other detergent and disinfectant wipes per day (Hanford, 2006).

Table 15
Crew hygiene wipe usage summary.

Date	All crew staterooms	Toilet room	Bathroom	Science Lab	Per day total	Per day Avg. per CM
20-Jun	24	10	5	0	39	5.6
21-Jun	20	11	5	0	36	5.1
22-Jun	26	15	5	0	46	6.6
23-Jun	30	13	1	0	44	6.3
24-Jun	21	11	3	0	35	5.0
25-Jun	22	14	7	1	44	6.3
26-Jun	23	14	0	11	48	6.9
27-Jun	15	12	0	21	48	6.9
28-Jun	18	11	2	12	43	6.1
29-Jun	25	12	2	0	39	5.6
30-Jun	31	10	2	14	57	8.1
Avg.	23.2	12.1	2.9	5.4	43.5	6.2

7.4.2. *Hand sanitizer*

Because hand sanitizer use also influences overall water consumption, it was tracked over the period from June 20 to July 10 inclusive. Those crewmembers that desired their own bottles were given fresh bottles on June 20 while additional all-crew bottles were available for use in the toilet room, bathroom and kitchen. Total usages are provided in Table 16 and equate to 9.2 mL for the entire crew per day or 1.3 mL/CM-day. Additionally, tabularized data provides the reader an idea of the location of greatest hand sanitizer use.

7.4.3. *Metered vs. unmetered monitoring*

As presented in Table 7 and discussed briefly, the crew used less water during the metered phases of the study than they did during non-detailed phases. In fact, the average per crewmember water use during the metered study phases was 11.13 L/day, while during the non-detailed phases the per crewmember use was 12.62 L/day. For a crew of seven this equates to a non-negligible total difference of approximately 10 L of water use per day. This is an interesting result in itself and agrees well with terrestrial water use data. In 1999, Canadian residential clients equipped with metered water systems used approximately 290 L/day while unmetered clients used approximately 430 L/day, a difference in use of over 30% (Environment Canada, 2000). The definition of “metered” in this instance is that the client is priced per volume of water use, while in the unmetered case the client pays a flat rate. Though not completely analogous to the on-orbit case, if astronauts know that their specific water use is being monitored by

Table 16
Hand sanitizer usage by location between June 20 and July 10 inclusive.

Location	Amt (mL)
Bathroom	59
Toilet	55
Kitchen	25
All crew staterooms	55
Total	194

the ground, it creates extra incentive to use less water. Though undemanding, completing the simple checklist following each water use may have on occasion also dissuaded crewmembers from using water. In all, the monitoring program did in no way, reduce crewmember usage to the point where their comfort was affected, but crewmembers did become in general more conservative than they were during the unmonitored phases. Implementing a real-time monitoring system into future spacecraft may provide added incentive for crewmembers to conserve water and may result in water use savings on the order of 10%, as demonstrated in this study.

7.4.4. Effect of EVA and exercise on crew water use

The influence of EVA on total water usage was investigated by logging field traverse information in conjunction with nominal water use data. As space-operational space suits and associated technologies were not used during this expedition, water use losses due to potential space suit life support system design and airlock venting were not considered. These losses are very technology dependent and an attempt to include them would not have increased the accuracy of this study. Additionally, suits for long duration Mars surface stay missions will probably differ from past and current suits in that they are unlikely to use water sublimation for heat removal (Pu et al., 2004). The definition of EVA duration used in this study is the time between when the hatch was opened for exit of the habitat airlock until when the hatch was closed upon reentry into the airlock. Total water use versus EVA duration for the period of May 26–June 23 is plotted in Fig. 9. Additionally, exercise duration is included in this plot. In both cases the durations presented are for the whole crew for a given day. For example, if three crewmembers went out on traverse for a period of 4 h, the total EVA duration would be 12 h for that given day.

As is apparent from Fig. 9, there is no obvious relation between total crew water use and EVA or exercise duration as would be evidenced by peaks of EVA duration or exercise durations matching in time with peaks of water use. In fact, if all collected EVA and exercise data is utilized, it is found that there is no statistically significant correlation between total water use and EVA duration ($DOF = 81$, significance of correlation = 0.05, two-tailed $\Rightarrow 0.0357 < 0.217$ critical coefficient). Further, a similar non-statistically significant correlation result is found for exercise duration and total crew water use ($DOF = 44$, significance of correlation = 0.05, two-tailed $\Rightarrow 0.0744 < 0.305$ critical coefficient). Nevertheless, study results do show that drinking water specifically is correlated with EVA and exercise duration ($DOF = 20$, significance of correlation = 0.05, two-tailed $\Rightarrow 0.756 > 0.423$ critical coefficient) and this result is statistically significant.

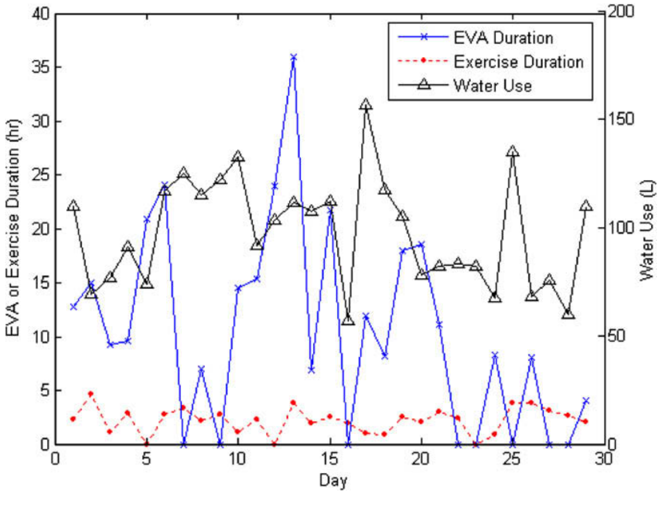

Fig. 9. Daily water use vs. daily EVA and exercise duration.

7.4.5. Science water

Water required for science related tasks will be heavily dependent on mission specific scientific content and chosen experiments. Though the scientific scheme of FMARS2007 may not precisely mimic an early planetary Mars mission in terms of objectives and employed science equipment, data was collected to help better bound baseline estimates. Water was used in the following ways during the expedition: distilling for solutions, washing of rocks, sieving, sterilizing by boiling and the general cleaning of science equipment. Each of these uses may be required in a laboratory on the Moon or Mars. The collection of science water use data turned out to be extremely positive as it demonstrated that designers should expect a large variation in science water use over the course of an expedition, regardless of the chosen experiments. This is not surprising, as there will be mission phases where very little science is conducted and phases where a great deal of science is conducted. Furthermore, some experiments are likely to be more water intensive than others and as there will be different priorities for different scientific investigations over the expedition, there will be variation in use. As is evident from Tables 8 to 11, the End of Expedition phase averaged over 3 L of science water while the other mission phases all averaged no more than 0.5 L. This was primarily a result of the fact that a large number of studies had to be concluded prior to departure from Devon Island. A similar situation may arise on a manned Mars mission, as the crew will not have the capacity to return all of the collected samples to the Earth and thus the bulk of the analyses will need to be conducted on-site, resulting in a ramp up in science for end of mission analyses.

7.4.6. End of Expedition phase

The End of Expedition phase, unlike the other phases, was conducted such that total crew water use was restricted to 70 L/day. Basic results of this phase are presented in Table 11. The chief finding during restricted use shows that while crew usage averages are on this order, particular days may require significantly more water; other days may require significantly less than this 70 L/day average. Additionally, if the crew understood that 70 L was all the water available for a given day, they would tend to purposely omit tasks such as clothes wash and shower to ensure sufficient water was available for required or higher priority purposes: drinking water, food preparation, hand/face, oral, etc. Another confounding factor is that tasks such as clothes wash and shower typically occurred during the late hours of the evening, sometimes after midnight (and therefore technically on the following day). This is not an ideal operational model to follow, as there is significant disruption in schedule efficiency. In all, the End of Expedition phase demonstrated that 70 L/day total crew use (10 L/CM-day), though nearly sufficient, is not reasonable for long duration space missions.

7.5. Comparison of study results to current literature

An extensive literature review was conducted to determine estimated water usage values for all of the various water use categories considered in this study. The bulk of the current literature on suggested water use values stems from one sole source (NASA, 1991). Hanford (2006), Dussap (2003), Wieland (1994), Larson and Pranke (1999), NASA (1995, 1996), Levri et al. (2001), Golub and Wydeven (1992) have all used this reference for their assumptions with minor variations. These variations include Levri et al. (2001), who assume 6.40 L/CM-day for shower water while NASA (1991) estimates 2.72 L/CM-day. Golub and Wydeven (1992) list 1.81 L/CM-day for hand and face compared to 4.09 L/CM-day and suggest 5.44 L/CM-day for shower water. The shower water value is likely in error as this is the identical value listed for dish wash. Finally, NASA (1995) lists 5.45 L/day for the total of hand/face, oral and shower water, where NASA (1991) assumes a slightly elevated rate. Other recent references do suggest differing values and these are presented in the additional columns of Table 17 which compares FMARS2007 study results to current literature for nominal 24-h days. Verostko et al. (1997) presents water balance data from the four crewmember LMLSTP Phase II, 30 day integrated test conducted in 1996. The LMLSTP was able to capture categorized water use data in the majority of categories by incorporating a water outlet for each of the various water use categories (e.g. use ports specific for hand washing, etc.). As an additional comparison, it is interesting to note the design requirements being used by the European Space Agency for the water system at Concordia Station, Antarctica, use 26 L/CM-day; even with additional requirements such as toilet flush water this is considerably higher than the water used per crewmember during the FMARS2007 expedition (Battrick, 2004). As a final note, several of the presented current literature values depend on specific chosen mission architecture assumptions and should be referred to individually for specifics. For example, though disposable meal preparation packages and dishes are suggested in several initial sortie and early planetary base architectures, thus reducing dish wash water, they have the potential to impact the mission negatively in other ways and thus reference assumptions which most resemble those assumptions used during the FMARS2007 simulation are used for comparison.

Table 17
Categorized water use study results compared to current literature.

Usage type	FMARS 2007	NASA (1991)	Verostko et al. (1997)	Philistine (2005)	Bobe et al. (2007)
Water use (L/CM-day)					
Drinking	2.59	1.62	1.77	2.1	2.2
Food prep.	1.03	0.76	0.68		
Hand/face	0.64	4.09	3.64	0.2	0.2**
Shower	1.08	2.73	6.36		6.0***
Oral	0.46		0.36		0.2**
Dish wash	3.54	5.44*			
Clothes wash	1.95	12.50	12.50		6.0***
Shaving	0.05				
Cleaning	0.02				
Science	0.04				
Engineering	0.02				
Plant growth	0.10				
Medical	0.00				

* Value from Hanford (2006) as no estimation provided in NASA (1991).
** Value a summation of hand/face and oral (i.e. hand/face + oral = 0.2 L/CM-day).
*** Value a summation of shower and clothes wash.

Several significant categorized differences exist in Table 17 between results from this study and current literature. Current literature suggests close to three times as much shower water is required than used during this study. The difference is primarily based upon an assumption of one shower per 2 days in NASA (1991) whereas the FMARS2007 crew was sufficiently content with one shower per week. Though the general assumption of one load of laundry per crewmember per week used during FMARS2007 is aligned with the frequency presented in literature, water use values differ significantly. As discussed, clothes wash water is highly technology dependent but even with the assumption of an extremely water efficient washer, clothes wash water is still estimated at 7.33 L/CM-day (Hanford, 2006). Hand/face wash water also shows a significant difference from literature and, as it is not reliant on technology, can be taken at face value, and demonstrates that considerably less water is required than has been proposed.

The FMARS2007 results shown in Table 17 were generated from the data in Tables 8 to 10 while accounting for differences in DAQ system and log sheet data as displayed in Table 12. Although the crew operated more or less nominally and comfortably during the End of Expedition phase, the authors decided not to include these values, given the potential confounding factors discussed above. In all, this study suggests that a long duration planetary surface crew operating on a 24-h cycle should require an average total of 11.50 L/CM-day with a standard deviation of 2.94 L/CM-day, while one operating on the slightly longer Martian day should require approximately 12.12 L/CM-sol with a standard deviation of 3.43 L/CM-sol. These are the totals as shown in Table 7. Recall that the tabulated values in Table 17 are based upon total water use during metered days and that unmetered days resulted in slightly higher usage rates. Therefore, these values should provide a reasonably accurate estimate for nominal crew water utilization for long duration planetary surface stay missions, as FMARS2007 demonstrated that even the metered usage values provide sufficient comfort and still represent unrestricted crew use. It should be noted that these values must be adjusted for other uses of water which were not required during the FMARS2007 expedition, including toilet flush water, leakage, sublimation cooling for EVA, process water losses and other architecture/technology dependent effects. Additionally, each specific categorized usage provides only a baseline for future use estimates and will be highly dependent on whether assumptions for future missions match the assumptions of this study. For example, if an aqueous dish washing machine is incorporated into future spacecraft the FMARS2007 study result may or may not be applicable for nominal operations. This is due to the dish washer requiring potentially more, or potentially less, water use than washing dishes by hand, as well a reduction in the variation in dish washing water use between crewmembers and thus on a day-to-day basis. Nonetheless, there is always the possibility that the dish washing machine will break down and the FMARS2007 numbers will be useful for this off nominal case. In general, off nominal cases such as degraded or emergency conditions may differ substantially from those presented in Table 17 and, depending on accepted tradeoffs and risk analysis, could be the design driver for total mission water.

Finally, it is important to recall that this study set out to determine the input water required by humans. It did not address in any way the various output forms, such as respired or perspired water, urine, etc.

8. Discussion

Though detailed quantitative water results were obtained, several qualitative points are also relevant for discussion. Firstly, all crewmembers were comfortable with the once a week shower rotation, despite the close quarters and regular physical exertion. It is certain that additional showers would not have been contested but from the perspective of sufficient comfort levels, they would have been a luxury. There were, however, several instances, during mid-summer when habitat temperatures were excessively warm, when the crew expressed a desire for additional showers. As external environmental factors will be of less importance in the accurately controlled internal environment of future long duration spacecraft, this particular problem should not be an issue. It is also worthwhile to report that the crew was sufficiently happy with washing clothes by hand and should this be required on long duration missions it should not pose excess stress to the crew.

8.1. Lessons learned relating to categorized water use studies

Several important lessons were learned during the design and implementation of this water utilization study. These items have been divided into separate categories and should provide additional background for improving future water utilization studies.

8.1.1. Sensor turndown ratio

Flow meters need a wide dynamic rate/high turndown ratio to be capable of monitoring very low flow rates (e.g. oral) to very high flow rates (e.g. shower). This is especially important when water pressure can be lost due to pump failure – if the sensor is not able to read at such low flow rates data will be lost. A different flow meter that had a turndown ratio of 0.5–5.0 GPM was initially tested during a two week training expedition to the Mars Desert Research Station and proved to be inadequate in terms of dynamic range. The flow meter that was used in the final study, OMEGA FTB4605, provided a high turndown ratio of 0.15–13 GPM (86.7 times), whereas typical flow meters have ratios in the 10 times range.

8.1.2. Multiple sensor sensing system vs. single master sensor

During the 2-week training expedition, a single master sensor on the outlet of the master reservoir was tested to see if it would suffice for monitoring all categorized water use. It soon became clear that this scheme would not be adequate due to the very high occurrence of simultaneous draws from different water outlets. A single sensor does not easily allow the separation of the volumes of these water calls. Moreover, a single master sensor would not allow differentiation between cold and hot water use demands. In a similar vein, though no accuracy issues arose during this study, it may be worthwhile to complement the flow meters with reservoir level sensors (e.g. Pepperl + Fuchs Ultrasonic Sensors, which were considered for this study) to provide additional redundancy and error checking.

8.1.3. Reducing missed data

As exhibited in Table 12, there was some discrepancy between the checklist categorized water data and the total water use data. Minimizing the number of missed records could be better accomplished through several means. The first is the use of cameras in the area of water outlets. These ensure that, if the crewmember forgets to record appropriate data, the video/images can be analyzed to determine the missed use. It should be noted that the installation of cameras in the habitat would likely not help prevent missed data in the bathroom as this is not an appropriate location for a camera. A webcam was deployed and worked well for this purpose in the area of the kitchen sink during the end of the Mars Time detailed phase. Even more beneficial would be a way to automate the checklist records so crewmembers could simply either flip a toggle switch or press a touch screen to select the category of use. This would allow electronic data to be collected immediately. This usage confirmation could be a requirement for water use; that is, the crewmember would not be able to draw water from the system during these detailed study phases until a button or toggle switch is activated. Though somewhat more complex to implement, this system would result in no loss of categorized water data.

8.1.4. Data analysis time

As is evident from the Data Flow and Software section, transcribing the written results to electronic format and then integrating them into the logged sensor data is very labour intensive. In fact, the time required for the conversion of writing to electronic data, the correlation of logged and recorded data, and the generation of useable datasets including tables and figures (does not include writing of software) was logged over the duration of the expedition. This amounted to approximately 145 h of devoted time throughout the expedition and another 35 h post-expedition. The bulk of this requirement was dealing with the data from detailed study phases which amounted to 35 out of a total of 86 days (87 Earth days). Thus, if 80% of processing was dedicated to the detailed study days, this would amount to just over 4 h of processing time per day. Future studies should attempt to reduce the amount of manual data entry and analysis. This could be accomplished by replacing the manual entry checklists by an automated system as described previously. Some simplicity could be had by implementing water use ports specific to each water use category. This can not easily be incorporated into the facility where the study will be conducted unless design forethought is had prior to facility construction. Additionally, implementing a water outlet for every different use category is unfeasible and would modify nominal crew operations and efficiency to an unreasonable extent.

9. Conclusion

This study is thought to be the first to carry out a true categorized examination of water use in all its various forms in a simulation of long duration space missions. Study results have implications to the life support system designer, and are especially applicable to long duration planetary surface stays. The FMARS 2007 expedition proved to be an advantageous venue for such a study due to the long duration nature of the expedition, the relevant space analogue environment, the facility volume and layout, the crew size and the schedule of daily activities including exercise and traverse tasking. This study suggests that in nominal operations a crewmember requires an average total water usage of approximately 11.50 L/day during a 24-h day cycle or 12.12 L/sol over a Mars sol. As these were unconstrained usage rates and this usage level was held for a period of close to 4 months, these values must provide adequate comfort levels and be of sufficient volume for ongoing operation. Study results suggest that current long duration planetary surface crew water utilization estimates are more than two times that required. Also of significance is that, though average usage is on the order of 11.50 L/day, water use can vary significantly between consecutive days and thus maximum foreseeable daily usage rates will become just as important in defining water stowage and buffer sizes. In fact, although the crew operated nominally under the 70 L/day total crew daily usage constraint during the End of Expedition study phase, crew compromises during this period (e.g. delaying high water usage tasks such as clothes washing) suggest that the 70 L/day limit was too low for long term operation. Additionally, this study addressed nominal operations and did not consider degraded or emergency conditions which can differ significantly and also drive water system design. Results of this study should also provide new baseline data for variation of water usage over a given day, effects of the implementation of a monitoring system on water use as well as estimates of categorized water use compared to current literature.

Acknowledgements

This work was carried out with the aid of a grant from the Canadian Space Agency, Longueuil, Quebec, Canada. Arctic logistics support was provided by the Polar Continental Shelf Project. Mars Society International and Mars Society Canada are acknowledged for overall project management and support of FMARS2007. Finally, Paul Graham provided technical aid for on-site monitoring system deployment.

References

Battrick, B. Water recycling systems for the Antarctic Concordia Station. European Space Agency Publications Division, BR-2175, 2004.

Bobe, L., Samsonov, N., Gavrilov, L., Novikov, V., Tomashpolskiy, M., Andreychuk, P., Protasov, N., Synjak, Y., Skuratov, V. Regenerative water supply for an interplanetary space station: the experience gained on the space stations “Salut”, “Mir”, ISS and development prospects. Acta Astronaut. 61, 8–15, 2007.

Colombo, G.V., Putnam, D.F., Thomas, E.C. Water management results for a 90-day space station simulator test. ASME 71-AV-6, 1971.

Dussap, C.G. REGLISSE: review of European ground laboratories and infrastructure for sciences and support of exploration–TN3: definition of the ideal facility for life support issues. Eur. Space Agency, 2003.

Golub, M.A., Wydeven, T. Waste streams in a typical crew space habitat: an update. Ames Research Center. NASA-TM-103888, 1992.

Environment Canada. Municipal water use database. Indicators and Assessment Office, SOE Bulletin No. 2001-1, 2000.

Hanford, A.J. Exploration life support baseline values and assumptions document. JSC. NASA-CR-2006-213693, 2006.

Larson, W.J., Pranke, L.K. Human spaceflight mission analysis and design. McGraw-Hill, pp. 124–125, 1999.

Lee, P., Osinski, G. The Haughton-Mars Project: Overview of science investigations at the Haughton impact structure and surrounding terrains, and relevance to planetary studies. Meteoritics & Planetary Science 40, 1755–1916, 2005.

Levri, J., Ewert, M., Kloeris, V., Perchonok, M., Peterson, L., Swango, B., Toerne, M.E., Vittadini, E. Food system trade study for an early Mars mission. SAE Technical Document 2001-01-2364, 2001.

Lim, D., Douglas, M. Limnological Characteristics of 22 Lakes and Ponds in the Haughton Crater Region of Devon Island, Nunavut, Canadian High Arctic. Arctic, Antarctic, and Alpine Research 35, 509–519, 2003.

NASA. Advanced life support program requirements definition and design considerations. JSC. NASA-CTSD-ADV-245, 1996.

NASA. Environmental control and life support system architectural control document. NASA-SSP-30262 Rev D. Space Station Freedom Program Office, 1991.

NASA. Man-systems integration standards. NASA-STD-3000, 1995.

NASA. Preliminary results from an operational 90-day manned test of a regenerative life support system. Langley Research Center. NASA SP-261, 1970.

Osburg, J. Crew experience at the "Flashline Mars Arctic Research Station" during the 2003 field season. SAE Technical Document 2004-01-2369, 2004.

Osburg, J. Personal Communication, 2007.

Philistine, C.L. International Space Station water balance evolution. SAE Technical Document 2003-01-2692, 2003.

Philistine, C.L. International Space Station water usage analysis. SAE Technical Document 2005-01-2836, 2005.

Pu, Z., Kapat, J., Chow, J., Recio, J., Rini, D. Personal cooling for extra-vehicular activities on Mars. Space 2004 Conference and Exhibit, San Diego, CA, September 28–30. AIAA Paper 2004-5970, 2004.

Verostko, C., Pickering, K., Smith, F., Packham, N., Lewis, J., Stonesifer, G., Staat, D., Rosenbaum, M. Performance of the water recovery system during phase II of the Lunar-Mars Life Support Test Project. SAE Technical Document 972417, 1997.

Wieland, P.O. Designing for human presence in space: an introduction to environmental control and life support systems. MSFC. NASA-RP-1324, 1994.