ANALYSIS OF HOUSEHOLD WATER-USE BEHAVIOR FOR USE AS IAQ MODEL PARAMETERS

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ABSTRACT
In assessing exposure to indoor air contaminants, the understanding of population water-use behavior for indoor water-use activities as a function of demographic characteristics is vital to obtaining realistic exposure estimates. In response to the need for more specific and usable population based water-use data for exposure modeling, new data sources have been analyzed. Frequencies, durations, volumes and flowrates of showers, baths, clothes washers, dishwashers, toilets and faucets are presented, derived from analyses of the National Human Activities Pattern Survey (NHAPS) database, the Residential End Uses of Water Study (REUWS) database, the Residential Energy Consumption Survey (RECS) as well as from current literature and manufacturer information. Distribution parameters for water use behaviors are identified for use as inputs for modeling exposure to water borne contaminants.

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INDEX TERMS
Water use, Activity patterns, Modeling, Exposure, Indoor air

INTRODUCTION
A realistic assessment of exposure and risk to water-borne contaminants requires accurate summaries of water usage patterns. Currently, there are a few limited studies that analyze household water-use behavior; the leading resources are summarized in the Exposure Factors Handbook (U.S. EPA, August 1997). In response to the need for more specific and usable population based water-use data to be used as inputs for exposure modeling, water-use data from various databases and literature sources were extensively analyzed in the recent USEPA report entitled "Quantification of Exposure Related Water Uses for Various US Subpopulations" (Wilkes, 2002) to quantify water-use behavior for a variety of demographic groups for use in assessing exposure to water-borne contaminants. This paper summarizes those findings on the frequency, duration, volume and flowrate characteristics for showers, baths, clothes washers, dishwashers, toilets, and faucets.

Data sources analyzed for water- use behavior parameters are: The National Human Activity Pattern Survey (NHAPS) compiled from a 1992-1994 telephone 24-hour recall survey of a representative sample of the US population (over 9,300 respondents) (Klepeis et.al., 1996); the Residential End Uses of Water Study (REUWS) compiled from a 1996-1998 study of water-use data recorded by a data-logging device attached to the household water meters of

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approximately 1200 single-family homes (100 homes in 12 different municipalities) (Mayer et.al., 1998); and the Residential Energy Consumption Survey (RECS) compiled from a 1997 nationwide survey focusing on household energy use information (5,900 respondents) (USDOE, 1995). In RECS, household data were weighted to statistically represent the 101.5 million U.S. housing units. Statistics presented herein are calculated using the weighted data.

DISCUSSION

When applicable, the frequencies and duration data from NHAPS, REUWS and RECS, sorted by demographic characteristics (such as education, employment status, U.S. EPA region, etc), were analyzed and compared for each type of water use. After comparing the databases, it was concluded that databases based on recall surveys, like NHAPS and RECS, are reliable sources for frequency information of relatively infrequent events such as showers, baths, dishwasher and clothes washer use, but are unreliable in reflecting more frequent events such as faucet use. REUWS, which is based on analysis of waterflow signatures of household water meters, is an excellent source for water-use duration information. Overall, due to the manner in which the databases were compiled, NHAPS data are more reliable than REUWS for frequency information, while REUWS data are more reliable than NHAPS for duration information. NHAPS was compiled from a recall telephone survey of the respondents' activities of the previous 24 hours. Respondents appeared to be able to remember how many showers and baths they took, while they had difficulty estimating the durations of the events, as the duration values appeared to be overestimated and clustered around 5-minute intervals. Furthermore, the data was truncated as all survey responses for shower duration over one hour were recorded as "greater than one hour" instead of the actual number of minutes. In contrast, REUWS was compiled from direct mechanical measurements of water usage logged at household water meters and subsequent waterflow disaggregation by the software program, Trace Wizard, to determine individual water uses. REUWS contains measured values of duration, volume, and flowrates of the water-use events in its database. For this reason, REUWS provides very accurate duration data. However, REUWS has a few integral limitations that make it less reliable in reference to frequency data, such as the inability to discern which person is performing the water uses in question, and at times Trace Wizard mislabeled events, reporting water uses that were clearly unrealistic. In regard to the frequency of clothes washer and dishwasher use, the RECS database was the most reliable source as the survey questions were more straightforward than those asked for NHAPS. Dishwasher and clothes washer durations and volumes are best characterized using a combination of data from REUWS, manufacturers' data, and data from field experiments. Only REUWS provides usable information on faucet and toilet use.

SHOWERS AND BATHS

***Shower and Bath Frequency*:** Frequency statistics resulting from NHAPS analysis on shower and bath use are believed to appropriately represent the populations' behavior. Table 1 presents these results for men, women, and children ages 5-12 yrs. Although the impact is believed to be relatively small, potential biases must be recognized including the ability to recall events and biases due to perceived societal expectations. The overall household bath frequency based on the REUWS analysis is also presented for comparison purposes.

Shower Duration: Shower duration statistics resulting from REUWS analysis are believed to appropriately represent the length of showers for the given population. The lognormal distribution provides a good representation for the shower duration data since the data are positively constrained. The geometric mean and standard deviation, and arithmetic mean are presented in Table 2 for the various demographic groups. The shower durations reported in

NHAPS were found to be unreliable, as in comparison to other sources they appeared to be overestimated and 89% were reported at a five-minute interval (i.e., 5, 10, 15, or 20 minutes).

Bath Duration: NHAPS contains the best available dataset for bath durations, since surveys like REUWS contain only the amount of water used to fill the bathtub not the bath duration. Although there are significant biases in the dataset, the duration statistics are recommended until a more definitive study provides better information. The durations reported in NHAPS are biased by a multitude of factors, including round-off errors as approximately 94% of baths were reported with durations at a five-minute interval, and estimation errors whereby a comparison with other shower duration studies indicates that duration responses in NHAPS tended to be overestimated. The NHAPS bath duration data are fitted to a lognormal distribution with results shown in Table 2.

Shower and Bath Volume and Flowrate: REUWS shower volume and flowrate data were analyzed and fit to lognormal distributions as shown in Table 2. However, as with other REUWS data, these data may be impacted by misclassification and single events reported as multiple events. Bath fill behavior and volume is not well enough understood to make recommendations based on the REUWS data. However, general dimensions of standard bathtubs are well understood, holding approx. 210-250 Liters (55-65 gallons) of water, when filled to the overflow, which is likely reduced by 20-30% due to the bather's body volume.

In general, the analysis showed that age significantly influenced shower and bath frequency and duration. The frequency of showering and bathing reported in NHAPS agreed reasonably well with previous studies; however, durations of these events were found to be significantly longer. The frequency of showering reported in REUWS was slightly less than that reported for NHAPS, though this may be due to NHAPS reflecting all showers taken during the day including those taken at work or at health clubs, while REUWS only recorded showers taken at home. The durations of showers reported in REUWS are consistent with other studies.

Table 1. Mean Frequency of Shower and Bath Use (Events per Person per Day)

	Men (N) 18-48 yrs	Women (N) 18-48 yrs	Children (N) 5-12 yrs	All (N)	All (N)
Data Source	NHAPS	NHAPS	NHAPS	NHAPS	REUWS
Shower Frequency	1.24 (1023)	1.12 (1086)	0.55 (329)	0.98 (4608)	0.82 (2947)
Bath Frequency	0.21 (1021)	0.38 (1082)	0.48 (336)	0.32 (4591)	Unknown

CLOTHES WASHERS

Frequency. The RECS database proved to be the most reliable resource for clothes washer use frequency data, as its data directly reflects the number of loads of clothes washed in the household per week. In contrast, the NHAPS data was not useful for two major reasons: the data reflected only the washing done by the survey respondent, and it was not clear whether the answer reflected the number of loads washed or the number of days per week the wash was done regardless of the number of loads done each day. Based on an analysis of RECS data, the number of loads of laundry washed per household per week increases with an increasing number of occupants in the household as shown in Table 3.

Table 2. Duration, Volume and Flowrate Statistics for Showers and Baths

	N	Geometric		Arithmetic
		Mean	St. Dev.	Mean
Showers (All, REUWS)				
Shower Duration (min)	3241	6.8	0.49	7.7
Shower Volume, L (gal)	3241	59.8 (15.8)	0.56	73.1 (19.3)
Shower Flowrate, L/min (gal/min)	3241	7.6 (2)	0.46	9.1 (2.4)
Baths (NHAPS)				
Bath Duration : All (min)	4591	17.6	0.63	20.9
Men, 18–48 yrs (min)	1020	17.2	0.69	20.8
Women, 18–48 yrs (min)	1081	17.8	0.72	21.5
Children, 5-12 (min)	328	18.6	0.51	20.8
Bath Volume, L, (gal)	n/a	n/a	n/a	189 (50)*
Bath Flowrate (REUWS) L/min (gal/min)	1966	16.6 (4.4)	0.54	18.5 (4.9)

*estimated based on typical bathtub size

Table 3. Mean Frequency of Clothes Washer Use (RECS, N=5,900 households)

Number of Occupants	1	2	3	4	5 or more	Overall
Per Household (loads/week)	3.2	5.2	6.8	8.5	9.2	6.1
Per Capita (loads/week)	3.2	2.6	2.3	2.1	1.8	2.3

Clothes Washer Duration and Volume. In regard to duration, REUWS provides data on the durations of the individual cycles (washes and rinses), which can be combined to determine the time it takes from the start of the first fill until the end of the last fill. However, REUWS does not provide data on the duration of the entire event, which would include the time to complete the final agitation and spin. In order to characterize the entire clothes washer duration, various sources were analyzed. For individual cycle duration information (wash fill, rinse fill), the REUWS data was used. For information on the agitation and spin durations, data from timed experiments on two typical top-loading machines were used. These values are provided in Table 4. According to the REUWS data, the fill (1st cycle) and first rinse (2nd cycle) are 100% likely to occur. The second (3rd cycle) and third rinses (4th cycle) are 18.7% and 0.8% likely to occur. Weighting the duration values for these additional rinses, the total duration of the washing event in this configuration was calculated. Table 5 presents the average volume of water used and total duration of a typical clothes washer event based on information presented in Consumer Reports (July 1998, July 1999, August 2000).

Table 4. Mean Volumes and Durations for Typical Top-Loaded Clothes Washer Cycles

Cycle 1				Cycles 2, 3, 4				
Volume	**Duration (minutes)***			**Volume**	**Duration (minutes)***			**Total****
L (gal)	Fill	Agitate	Drain	L (gal)	Fill	Agitate	Drain	**Duration**
62.8 (16.6)	3.8	12.0	4.0	57.9 (15.3)	7.5	4.0	8.0	43.1 min

* Based on experiments on Kenmore 70 series 1992 and 90 series 1999 set to high-water level.
** Cycles 1 & 2 are 100% likely, cycle 3 is 18.7% likely, and cycle 4 is 0.8% likely (REUWS).

Table 5. Mean Volumes and Durations for Clothes Washer Events

Machine Type	Volume L/load (gal/load)	Duration min/load	Citation
Top-Loading (before 1999)	155 (41)	43	Consumer Reports (July 1998, July 1999)
Top-Loading (2000 models)	124.9 (33)	45	Consumer Reports (Aug. 2000)
Front-Loading	102.2 (27)	64	Consumer Reports (July 1998, Aug 2000)

DISHWASHERS

As compared to other water sources in a household, dishwasher uses represent a relatively small source in respect to water-borne contaminant exposure because of the infrequent usage, small water volume, and the relatively sealed washing compartments. As such, the exposure resulting from dishwasher use can be expected to be a very small portion of an occupant's overall exposure to water borne contaminants.

Frequency of Dishwasher Use. To represent the frequency of dishwasher use, the most reliable data was judged to be from the RECS analysis, because the RECS survey question reflected household use, while the NHAPS survey question reflected dishwasher use of only the respondent. However, the RECS data did not capture the lower frequencies of use, as the response choices were either: "Daily", "4 to 6 loads per week", or "less than 4 loads per week." In analyzing this data, the frequency was calculated assuming the median value for each frequency range. Considering that 56.3% of the respondents answered "less than 4 loads per week", this data clearly lacks definition. According to the RECS analysis, shown in Table 6, frequency of dishwasher use per capita decreases as family (or household) size increases.

Table 6. Mean Frequency of Dishwasher Use (RECS, N=5,900 households)

Number of Occupants	1	2	3	4	5 or more	Overall
Per Household (loads/week)	2.5	3.4	3.8	4.6	5.1	3.7
Per Capita (loads/week)	2.5	1.7	1.3	1.2	1.0	1.4

Dishwasher Duration and Volume. Based on the information available from dishwasher manufacturers, the typical dishwasher event is comprised of approximately 5 fills (incl. washes and rinses). Assuming the "Normal Wash" option across brands listed in various manufacturer-supplied data and from Consumer Reports (March, 1998), the overall average duration of a dishwasher load (including drying time) was 100 minutes and the total volume of water used was 30.3 liters (8 gallons). See Wilkes, 2002 for details.

TOILETS

Analysis of REUWS data provides reliable information for toilet flush frequency, and toilet tank fill duration, volume and flowrate. The NHAPS survey did not include questions about toilet use. From the REUWS data analysis, it is estimated that, on average, a person flushes 5.5 times per day. However, it must be kept in mind that the REUWS database only contains water-uses that occurred in the home and therefore doesn't account for toilet uses at work or elsewhere during the day. The amount of water that toilets use to flush has dramatically decreased due to conservation efforts and mandated plumbing codes. Early models used about 19-26 liters (5-7 gallons) per flush, while newer toilets manufactured after 1992 are required by U.S. law to use only 6 liters (1.6 gallons) per flush. The summary results from the REUWS analysis on toilet tank fill volume, duration, and flowrate are presented in Table 7. It is safe to assume that as years pass, the average volume of water used per flush in any given U.S. population will decrease as older toilets are replaced with more efficient toilets.

Table 7. Toilet Flush Characteristics (REUWS)

Parameter (N)	Mean	St. Dev.
Frequency (22,582 days)	5.5 flushes/person/day	3.23
Toilet tank volume (245,382 flushes)	13.2 liters (3.48 gallons)	1.18
Toilet tank fill flowrate (245,382 flushes)	14.8 liters/minute (3.9 gallons/minute)	1.31
Toilet tank fill duration (245,379 flushes)	71.4 seconds	29.77

FAUCETS

Faucet usage is probably the most difficult household water use to characterize in general terms because each water use may differ greatly from the next in its duration, volume, flowrate and temperature. However, the REUWS database is the best available source of frequency, volume, duration, and flowrate information regarding faucet use. Analysis shows that frequency of faucet use is dependent on the number of occupants in the household, as the mean faucet uses per person per day decreases as the household size increases (Wilkes, 2002). This results from the many faucet uses that are house-related not individual-related, such as for cooking or cleaning. The general characteristics of faucet use are presented in Table 8.

Table 8. Faucet Use Characteristics (REUWS)

Parameter	N	Mean	Mode	Min.	Max.	St. Dev.
Frequency, uses/person/day	965 people	17.4	–	–	–	11.6
Volume per event, L (gal)	973,722 uses	2.6 (0.7)	0.38 (0.1)	0.0	142.3 (37.6)	3.8 (1.0)
Duration per event, seconds	973,717 uses	33.9	10.0	10.0	5400.0	45.6
Flowrate, L/min (gal/min)	973,722 uses	4.5 (1.2)	1.9 (0.5)	0.0	40.5 (10.7)	2.6 (0.7)

CONCLUSIONS

Linking the use of contaminated water with exposure and potential risk analyses can be accomplished using an exposure model that represents factors leading to contaminant release and contact. Such a model must represent the physical environment, the emission characteristics of the water appliances during their use, and the water-use and location behavior of the occupants. The water-use characteristics and distributions discussed and presented in this paper (from Wilkes, 2002) are analyzed such that the data can effectively be utilized by an exposure model (such as the Total Exposure Model (TEM)) when simulating realistic occupant water-use behaviors of various populations. Though the available databases provide significant information on water-use parameters, there is need for considerably more research in quantifying these behaviors.

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TECHNICAL REPORT DATA

16. Abstract

Chemicals brought into the home through the domestic water supply, result in human exposure via the three principal routes: ingestion, inhalation, and dermal contact. Disinfection byproducts resulting from the treatment of municipal water supplies lead to the formation of a mixture of organic compounds ranging from high to low volatility. The inhalation route has been shown to be the most significant route of exposure for the more volatile chemicals.

In assessing exposure to indoor air contaminants, understanding population water-use behavior for indoor water-use activities as a function of demographic characteristics is vital to realistic exposure estimates. Currently, there are few and limited studies that analyze household water-use behavior; the leading resources are summarized in the Exposure Factors Handbook (U.S. EPA, August 1997). In response to the need for more specific and usable population based water-use data to be used as inputs for exposure modeling, new data sources have been analyzed. Frequencies and durations of use of showers, baths, clothes washers, dishwashers, toilets and faucets are presented and compared for various demographic groups derived from analyses of the National Human Activities Pattern Survey (NHAPS) database, the Residential End Uses of Water Study (REUWS) database, the Residential Energy Consumption Survey (RECS) as well as from current literature and manufacturer information. Volumes and flowrates are also analyzed from REUWS for the various water uses. Distribution parameters for water use behaviors of various sub-population groups are identified for water uses to be used as inputs for modeling of exposure to water borne contaminants.

The results from the database analyses will be presented in the form of fitted distributions for water-use durations for the various sub-population groups. A summary of frequency of use parameters for all water uses, and volume and flowrate characteristics of clothes washers and dishwasher appliances are also presented.

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