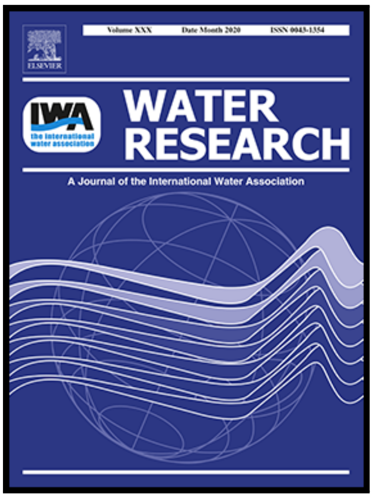


Investigating the Characteristics of Residential Hot-Water Consumption: a Worldwide Review

Filippo Mazzoni , Valentina Marsili , Mirjam Blokker ,
Stefano Alvisi

PII: S0043-1354(26)00790-6
DOI: https://doi.org/10.1016/j.watres.2026.126109
Reference: WR 126109

To appear in: *Water Research*

Received date: 26 January 2026
Revised date: 7 May 2026
Accepted date: 10 May 2026

Please cite this article as: Filippo Mazzoni , Valentina Marsili , Mirjam Blokker , Stefano Alvisi , Investigating the Characteristics of Residential Hot-Water Consumption: a Worldwide Review, *Water Research* (2026), doi: https://doi.org/10.1016/j.watres.2026.126109

Highlights:

- Systematic review of 59 databases on residential hot-water consumption
- Analysis of the most investigated hot-water consumption features
- Multi-level framework to compare available literature outcomes
- Hot-water consumption quantified at the household and end-use levels
- Available, open database of hot-water consumption data

Investigating the Characteristics of Residential Hot-Water Consumption: a Worldwide Review

Filippo Mazzoni[1], Valentina Marsili[1], Mirjam Blokker[2,3], Stefano Alvisi[4]

[1]Postdoctoral Researcher, PhD, Department of Engineering, University of Ferrara, Via Saragat 1, Ferrara 44122, Italy

[2]Associate Professor, PhD, TU Delft, Faculty of Civil Engineering and Geosciences, Stevinweg 1, Delft, CN 2628, The Netherlands

[3]KWR Water Research Institute, Groningenhaven 7, Nieuwegein, PE 3433, The Netherlands

[4]Associate Professor, PhD, Department of Engineering, University of Ferrara, Via Saragat 1, Ferrara 44124, Italy

Abstract

Residential Hot-Water Consumption (HWC) is a key component of the water–energy nexus at the household scale, and its accurate characterization is crucial for developing effective and sustainable water and energy management strategies, as well as for reducing the environmental footprint of the built environment. However, current knowledge of residential HWC is constrained by data fragmentation and methodological heterogeneity, underscoring the need for a comprehensive, standardized database to support robust comparative analyses across different contexts. In response to this gap, the present study provides a systematic and comprehensive literature review of residential HWC, synthesizing evidence from 77 scientific and technical sources referring to 59 distinct HWC databases. The investigation includes a preliminary phase examining available studies, their objectives, and levels of data aggregation, followed by a multi-level analysis at both the household and end-use (i.e. domestic fixture category) scales. This approach aims to explore HWC values, hot-water use parameters, and consumption profiles across multiple time scales. By providing a systematic comparison of HWC characteristics, assembling a consolidated open-access database, and identifying the underexplored areas, this review supports the derivation of transferable values and provides guidance for future research.

Keywords

Hot-Water Consumption; Residential Hot-Water Study, Hot-Water Database; Hot-Water Ratio; Hot-Water Profiles; Daily Variations; Monthly Variations; Water-Energy Nexus.

1. Introduction

Ensuring access to safe and reliable drinking water is a fundamental objective for modern societies (United Nations, 2010). However, potable water supply requires substantial environmental and economic resources, as treatment and distribution processes rely on significant raw-water withdrawals and energy-intensive operations (Zhao et al., 2025). In a context of growing pressure on freshwater systems and increasing energy footprints of water services (Khalkhali et al., 2021), optimizing the management and operation of supply systems, together with promoting the sustainable use of water resources, has become a critical priority (Wang et al., 2026). Achieving these goals ultimately depends on a robust understanding of how consumers use water; therefore, the characterization of water consumption – including volumes, temporal profiles, and composition of end uses (i.e. domestic fixture categories) – provides essential information for developing resilient and effective water-management strategies (Blokker et al., 2010; Cominola et al., 2019).

Over recent decades, technological advancements have significantly transformed the monitoring and analysis of water consumption, particularly in the residential sector. Smart metering technologies have enabled the transition from low-frequency, aggregate measurements to high-resolution datasets collected at the household scale, with increasingly fine temporal granularity—down to hourly, minute, or even second intervals (Clifford et al., 2018; Mazzoni et al., 2023a). Smart-meter data have been widely applied in the scientific literature to disaggregate residential water consumption into its major end uses (Mazzoni et al., 2023b), develop water-demand models (Pesantez et al., 2020), and assess behavioral and socio-technical drivers of consumption (Cominola et al., 2023). In parallel, smart meters have demonstrated substantial operational value, supporting utilities and consumers through applications such as leakage detection (Luciani et al., 2019), anomaly identification (Salomons et al., 2022), and personalized feedback on water use (Britton et al., 2013; Koop et al., 2021).

Beyond overall residential water consumption, a detailed characterization of its hot-water component – hereinafter referred to as *hot-water consumption* (HWC) – can help better understand the resource and energy implications of domestic water demand. In fact, HWC includes a substantial energy component due to the heating phase, making it a central driver of the water–energy nexus across multiple aggregation levels (Sousa & Meireles, 2022). At the national scale, for instance, in countries such as the Netherlands, the thermal energy required for domestic water heating can be nearly four times greater than that needed for drinking water production and distribution and for wastewater collection and treatment (Roest et al., 2010). At the building scale, improvements in insulation and heating-system efficiency are significantly increasing the relative share of energy attributed to HWC: in high-performance residential buildings, HWC can account for up to half of the total thermal energy demand (Verhaert et al., 2016; Kitzberger et al., 2019). Nevertheless, HWC can also affect overall domestic energy consumption and carbon emissions due to heat losses occurring along the plumbing system (Hall et al., 2024). In this context, distinguishing hot- from cold-water volumes enables the characterization of HWC statistics and profiles, supporting the design of efficient domestic water-heating strategies and the implementation of conservation, heat-recovery, and reuse measures, ultimately reducing the environmental footprint of water heating (Fuentes et al., 2018; Meireles et al., 2022).

Although significant efforts have been made over recent decades to investigate residential HWC, the existing knowledge remains fragmented. For instance, some recent studies estimate hot-water use indirectly from energy measurements (Graf et al., 2024), predict it using artificial-intelligence-based methods (Bayle et al., 2024), or infer potential volumes from total-consumption smart-meter data (Schaffer et al., 2024). While these approaches are suitable for energy assessments, they do not necessarily capture actual HWC volumes, hot-water use characteristics, or profiles. In contrast, several studies have assessed HWC through volumetric measurements in the field, providing descriptive parameters and profiles across households and end-use categories. Nevertheless, these datasets are dispersed, methodologically heterogeneous, and difficult to compare.

In a notable effort to collect the results of studies carried out over the last three decades, Fuentes et al. (2018) provide a broad overview of residential and non-residential HWC. With specific reference to the residential sector, the review characterizes HWC from different contexts worldwide together with the related technical standards, identifies the main drivers, and summarizes the modelling techniques currently applied to simulate HWC patterns in residential buildings. However, due to the wide scope of its objectives, the review places greater emphasis on the energy-performance perspective. In addition, the authors note that most empirical studies report HWC data – such as daily or annual volumes per building or per capita – which provide limited insight into the spatio-temporal variability and complexity of HWC. This highlights the need for more detailed information on hot-water use parameters (frequency of use, drawn volumes, and durations) as well as daily consumption profiles, which are typically required for the development of accurate demand models. In this context, technical standards for domestic plumbing design and energy-efficient water heating (e.g., CEN, 2017; ASHRAE, 2019) provide guidelines for estimating residential HWC. However, these are mainly based on synthetic data, and relying solely on this type of information may lead to a misrepresentation of actual system behavior. This underscores the need to prioritize direct field assessment (i.e. based on volumetric monitoring) of HWC and related profiles to capture actual operational performance and ensure reliable energy evaluations (Edwards et al., 2015; De Santiago et al., 2017).

Overall, these findings highlight a broader critical gap in the state of the art: the absence of a comprehensive and systematic database integrating HWC values, parameters, and profiles derived from direct field assessment across different contexts worldwide. Such a database is needed to support comparative analyses, improve model representativeness, and guide both water-demand and energy-performance assessments.

In light of the above, the present study innovatively provides a systematic and comprehensive review of residential HWC descriptive parameters and profiles as reported in the scientific and technical literature. From an operational standpoint, 77 studies on direct field assessment of HWC are reviewed, and the results from 59 associated databases are systematically compared at both the household and end-use scales. The study adopts a multi-level framework to address three specific objectives: (1) to compare HWC descriptive parameters and synthetize results into consistent benchmarks; (2) to address data fragmentation by assembling the reviewed datasets into an open-access database to support future research on residential HWC; (3) to identify key knowledge gaps and underexplored aspects in current research, thereby informing future studies and supporting further characterization of HWC.

2. Materials

This section presents the systematic review approach and discusses the initial insights obtained from the literature search. The analysis is grounded in a specific definition of HWC, here considered as the volume of water that reaches domestic end uses through the hot-water line of the domestic plumbing system. This water may be heated at the household scale (e.g., by boilers, heat pumps, or other systems) or supplied via a centralized hot-water distribution system, a configuration typically found in multi-apartment buildings. Consequently, water that is heated internally within individual fixtures or appliances by electric resistance (such as dishwashers and washing machines in most non-US contexts) is excluded from the analysis. This water is formally classified as cold water, as it cannot be detected by flow meters or monitoring devices installed on the domestic hot-water line.

2.1. Literature review

To ensure transparency and reproducibility, the review is conducted in accordance with the PRISMA guidelines (Page et al., 2021), the main steps of which are illustrated in **Figure 1**.

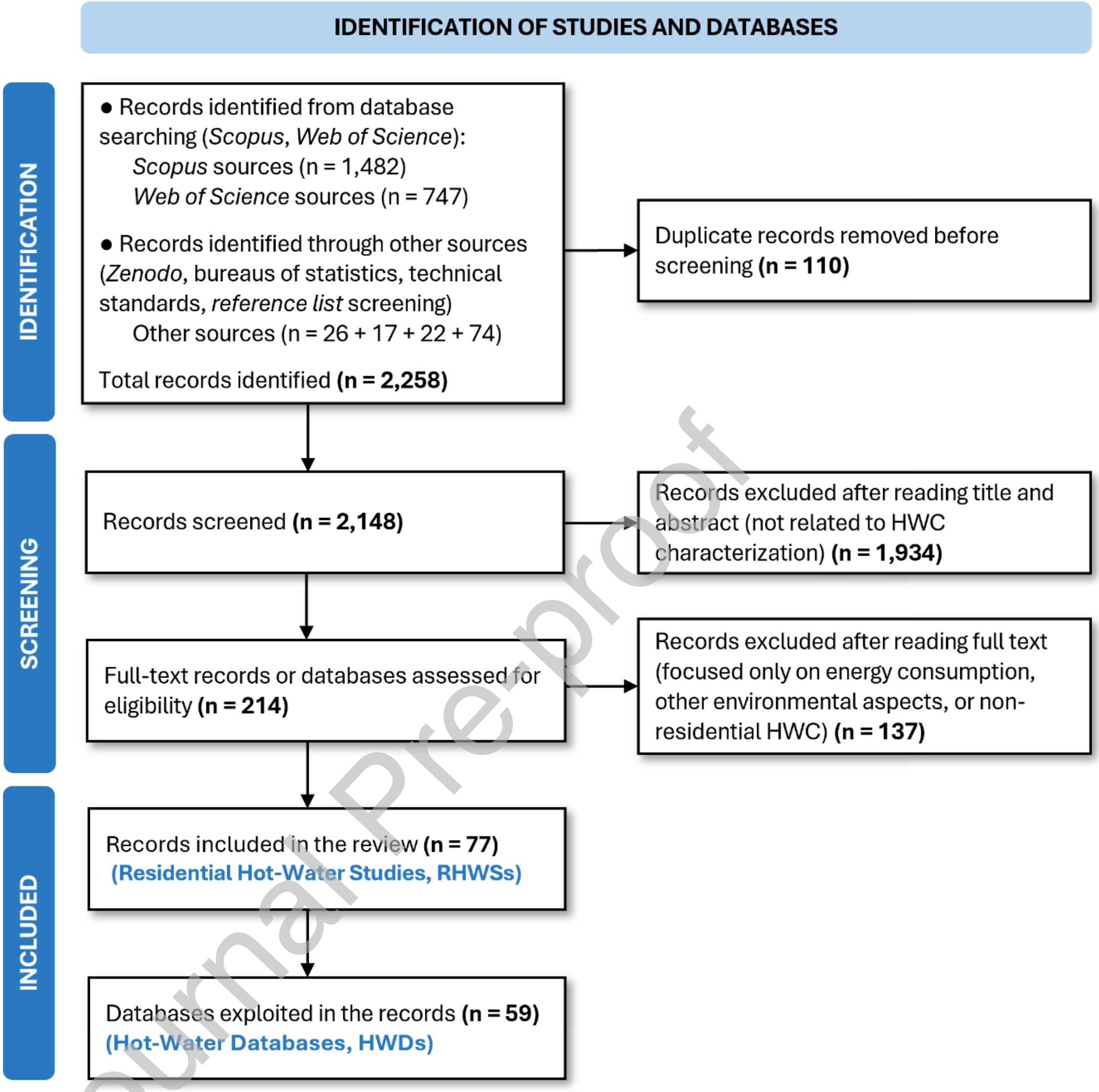


Figure 1. Layout of the PRISMA-based literature review process.

From an operational standpoint, the Scopus (Elsevier, 2025) and Web of Science databases (Clarivate, 2026) are consulted to identify relevant sources (i.e., scientific papers, reports, theses, and other grey literature) related to HWC. Specifically, the following combination of search terms and operators is used: *(hot AND water AND (consumption OR demand OR use OR usage)) AND (analysis OR characterization OR investigation OR assessment OR profile OR pattern OR domestic OR residential OR non-residential)*. Three criteria are applied to filter the results: (1) the research domain is restricted to engineering to exclude sources related to chemical, medical, or physical applications of hot water; (2) the source is required to be published in English; and (3) the term “water” is required to appear in at least one of the source keywords. Additional sources on HWC are identified through searches in the Zenodo database (Zenodo, 2026), consultation of international and national statistical bureaus, international and national technical standards and guidelines and backward reference screening of the selected sources.

In total, 2,148 sources are identified (i.e., 2.258 records, including 110 duplicates). These are screened by title and abstract to exclude records not related to quantitative assessments of HWC at the level of groups of households, individual households, or end uses, resulting in a subset of 214 sources. The set of sources is further refined by restricting it to the residential sector and to studies reporting quantitative HWC assessment relying on direct field assessment, i.e. volumetric data collected in the field (optionally coupled with temperature monitoring and/or interaction with users). Accordingly, studies focusing on non-residential HWC, as well as those estimating HWC exclusively from energy consumption data, are excluded. The exclusion of the latter is justified by the strong dependence of water-heating energy demand on inlet and outlet water temperatures; as a result, identical HWC values may correspond to substantially different energy consumption requirements depending on geographical context and seasonal conditions.

At the end of this process, a total of 77 studies on residential HWC conducted from the 1970s through 2026 and including measured hot-water data (hereinafter referred to as *Residential Hot-Water Studies*, *RHWS*s) are retained.

Each RHWS is individually reviewed to assess its specific contribution to the characterization of HWC. In particular, a preliminary analysis examines the main objectives of each study, the results of which are presented in **Figure 2** (in which the total number of occurrences exceeds the total number of RHWS because some studies addressed multiple objectives). The review also reveals that the 77 RHWSs correspond to 59 distinct HWC databases (hereinafter referred to as *Hot-Water Databases*, *HWD*s), with some databases used in more than one RHWS and others appearing in only one RHWS. An overview of the 59 HWDs identified – together with their main characteristics and the corresponding RHWS – is provided in **Table 1**.

Table 1. Overview of the 59 Hot-Water Databases (HWD) and the related 77 Residential Hot-Water Studies (RHWS) identified. Columns L1–L5 (household and end-use scale) refer to the levels of analysis which can be carried out for each HWD based on the information reported in the related RHWSs.

HWD	RHWS	STUDY AIM	LOCATION	HOUSEHOLDS SAMPLE SIZE	MONITORING PERIOD DURATION (AND MONTHS)	TEMPORAL RESOLUTION	AGGREGATION LEVEL	HWC DATA OBTAINMENT	HEATING SOURCE	CENTRALIZED HEATING SYSTEM	STORAGE SYSTEM (TANK)	INLET TEMPERATURE (°C)	OUTLET TEMPERATURE (°C)	END-USE TEMPERATURE (°C)	LEVELS OF THE ANALYSIS (HOUSEHOLD SCALE)					LEVELS OF THE ANALYSIS (END-USE SCALE)				
															L1	L2	L3	L4	L5	L1	L2	L3	L4	L5
1	Webster 1972 [a]	WWQ [a]	United Kingdom [a]	N/A	N/A	N/A	End use [a]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]	[a]
	Butler 1991	WWQ													✓					✓				
2	Perlman and Mills 1985	HWCD, HWCM, HWCQ	Canada	55	1-2 years	15 min	Household	HM	Electricity, gas, solar	No	Yes	N/A	54-60	N/A	✓			✓	✓					
	Becker and Stogsdill 1990	HWCQ													✓									
	Fairey and Parker 2004	HWCQ																✓						
	Chen et al. 2020	HWCM													✓									
3	Gilbert 1985 [b]	HWCQ [b]	United States [b]	110 [b]	1 year [b]	15 min [b]	Household [b]	HM [b]	N/A	N/A	N/A	N/A	N/A	N/A	[b]	[b]	[b]	[b]	[b]	[b]	[b]	[b]	[b]	[b]
	Becker and Stogsdill 1990	HWCQ																						
	Fairey and Parker 2004	HWCQ																						
	Chen et al. 2020	HWCM																						
4	Weihl and Kempton 1985	HWCQ, DGE	United States	7	12-78 days (various mo	1 min	End use	HM + TM	Electricity, gas	No	Yes	N/A	46-67	N/A			✓							

					nths)																			
	Kempton 1988	HWCQ			50-183 days (various months)										✓		✓			✓		✓		
5	Vine et al. 1987	HWCQ, HWCD	United States	48	4-6 months (Mar to Aug)	15 s	Household	HM+TM+I	Solar, other	Yes	Yes	N/A	N/A	58 (average)	✓			✓						
6	Milligan 1987 [c]	HWCQ [c]	Canada [c]	N/A	1 year [c]	15 min [c]	Household [c]	HM [c]	N/A	N/A	N/A	N/A	N/A	N/A	[c]	[c]	[c]	[c]	[c]	[c]	[c]	[c]	[c]	[c]
	Becker and Stogsdill 1990	HWCQ																✓						
7	Merrigan 1988	HWCQ	United States	98	1-2 years	15 min	Household	HM	Electricity, solar, other	No	Various	N/A	43-68	N/A	✓			✓						
	Becker and Stogsdill 1990	HWCQ																✓						
	Fairey and Parker 2004	HWCQ																						
	Chen et al. 2020	HWCM													✓									
8	Masiello and Parker 1992	RWEN	United States	171	N/A	N/A	Household	N/A	Electricity, gas, solar	No	Various	24	N/A	N/A										
	Bouchelle et al. 2000	RWEN		204								23	N/A	N/A				✓						
	Fairey and Parker 2004	HWCQ		N/A																				
9	Anderson et al. 1993	WC	United States	25	2 months (various months)	N/A	Household	HM	N/A	No	N/A	N/A	N/A	N/A	✓	✓								
10	Edwards and Martin 1995	EUWC, HWCD	United Kingdom	100	1 year	15 min	End use	EM	N/A	N/A	N/A	N/A	N/A	N/A		✓					✓			

11	Meyer and Tshimankinda 1996	HWCQ	South Africa	90	1 year	1 h, 1 month	Household	HM	Electricity	No	Yes	N/A	65°C	N/A	✓			✓	✓						
12	Papakostas et al. 1995	HWCQ	Greece	83	1 year	1 min	Household group	AM	Solar, other	Yes	Yes	N/A	N/A	42-45	✓			✓							
13	Abrams and Shedd 1996	HWCQ, RWEN	United States	27	10 months (Aug to Jun)	1 min, 15 min	Household group, household, end use	HM + TM	N/A	Various	N/A	15	N/A	N/A	✓				✓						
	Chen et al. 2020	HWCM																							
14	Lowenstein and Hiller 1998	HWCQ	United States	14	1 year	15 s	Household group, household, end use	HM + TM	N/A	Various	Yes	N/A	N/A	N/A	✓			✓		✓			✓	✓	
	Chen et al. 2020	HWCM		14																✓					
15	Meyer and Tshimankinda 1998a	HWCQ	South Africa	90	1 year	1 h, 1 month	Household	HM	Electricity	No	Yes	N/A	65	N/A	✓			✓	✓						
16	Meyer and Tshimankinda 1998b	HWCQ	South Africa	90	1 year	1 h, 1 month	Household	HM	Electricity	No	Yes	N/A	65	N/A	✓			✓	✓						
17	Sullivan and Parker 1999 [d]	WC [d]	United States [d]	N/A	N/A	N/A	End use [d]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	[d]	[d]	[d]	[d]	[d]	[d]		[d]	[d]	[d]	[d]
	Gleick et al. 2003	WC																				✓	✓		
18	Jordan and Vajen 2001	HWCM	Germany, Switzerland	N/A	N/A	1 min, 6 min, 1 h	End use	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓					✓			✓		
19	Mayer et al. 2000	EUWC, WC	United States	10	4 weeks (various months)	10 s	End use	HM + DC	N/A	No	Yes	13	40	N/A	✓	✓				✓		✓	✓		
	DeOreo and Mayer	EUWC,													[e]	[e]	[e]	[e]	[e]	[e]		[e]	[e]	[e]	[e]

	2000 [e]	WC [e]																							
	Aquacraft 2005 [f]	EUWC, WC [f]													f	f	f	f	f	f		f	f	f	f
	Abdallah and Rosenberg 2014	HWCM, RWEN																				✓			
	Chen et al. 2020	HWCM													✓					✓		✓			
	U.S. Environmental Protection Agency 2026	HWCQ																				✓			
20	Henze et al. 2002	DGE	United States	1	39 days (Mar to Apr)	1 s	End use	HM + TM	N/A	No	No	N/A	N/A	At least 45	✓		✓	✓		✓			✓		
	Chen et al. 2020	HWCM												-						✓					
21	Mayer et al. 2003	EUWC, WC	United States	10	4 weeks (various months)	10 s	End use	HM + DC	N/A	No	Yes	13	40	N/A	✓	✓				✓		✓	✓		
	Aquacraft 2005 [f]	EUWC, WC [f]													f	f	f	f	f	f		f	f	f	f
	Abdallah and Rosenberg 2014	HWCM, RWEN																				✓			
22	Knight et al. 2007	HWCQ, HSD	Canada, Finland, France, Germany, Portugal, Spain, Switzerland, United Kingdom, United States	N/A	N/A	1 min, 5 min, 15 min, 60 min	Household	N/A	Gas, other	Various	N/A	N/A	Various (30-60)	N/A	✓			✓							
	IEA 2008	HWCQ, RWEN		N/A									Various (45-50)	N/A				✓							
23	CEC 2008	HWCQ, R	United States	41	2 weeks-27	N/A	Household	HM	Gas, other	Various	Vario	N/A	46-57	N/A	✓		✓	✓							

		WEN			months						us													
24	DEFRA 2008	HWCQ, RWEN	United Kingdom	124	1 year	10 min	Household, end use	HM + TM	Gas	No	Various	15	52 (average)	N/A	✓		✓	✓	✓	✓				✓
	Gelažanskas and Gamage 2015	HWCM		95			Household																	
25	Widén et al. 2009	RWEN	Sweden	34	Up to 2 years	1 min, 10 min, 1 h	Household, end use	EM	Electricity	No	Yes	10	N/A	N/A										
26	Thomas et al. 2011	HWCQ	Canada	74	2-3 weeks (various months)	2 s, 4 s	Household	HM + DC	N/A	No	Various	N/A	N/A	N/A	✓		✓							
27	Bagge and Johansson 2011	DGE	Sweden	72	6 days (Jan)	6 s	Household group	AM	N/A	N/A	N/A	N/A	N/A	N/A				✓						
28	Schoenbauer et al. 2012	HWCQ, RWEN	United States	10	12-15 months	1 s	End use	HM + TM	N/A	No	N/A	N/A	N/A	N/A	✓		✓	✓		✓			✓	

Table 1 (Continued). Overview of the 59 Hot-Water Databases (HWD) and the related 77 Residential Hot-Water Studies (RHWS) identified. Columns L1–L5 (household and end-use scale) refer to the levels of analysis which can be carried out for each HWD based on the information reported in the related RHWSs.

HWD	RHWS	STUDY AIM	LOCATION	HOUSEHOLD SAMPLE SIZE	MONITORING PERIOD DURATION (AND MONTHS)	TEMPORAL RESOLUTION	AGGREGATION LEVEL	HW DATA OBTAINMENT	HEATING SOURCE	CENTRALIZED HEATING SYSTEM	STORAGE SYSTEM (TANK)	INLET TEMPERATURE (°C)	OUTLET TEMPERATURE (°C)	END-USE TEMPERATURE (°C)	LEVELS OF THE ANALYSIS (HOUSEHOLD SCALE)					LEVELS OF THE ANALYSIS (END-USE SCALE)				
															L1	L2	L3	L4	L5	L1	L2	L3	L4	L5
29	Bøhm 2013	RWEN	Denmark	1370	15 months	5 min	Household group	AM	District heating, other	Yes	Various	10	55	N/A										
30	Gerin et al. 2014	HWCQ	Belgium	8086	3-7 years	10 min, 1 month	Household group, household	HM	N/A	Yes	N/A	10	60	N/A		✓			✓					

31	Henderson and Wade 2014	HWCQ, RWEN	United States	5	4-9 months (Dec to Jun)	5 s	End use	HM + DC	Gas, other	No	Various	N/A	40-48	N/A	✓		✓			✓		✓
32	Ahmed et al. 2015	HWCQ	Finland	182	2 years	1 day	Household	HM	District heating, solar	Yes	Yes	7	55	N/A	✓	✓			✓			
33	Chao et al. 2015	WC	Australia	59	3 years	1 min	Household	HM	Solar	N/A	Yes	N/A	60	N/A	✓	✓		✓	✓			
34	George et al. 2015	HWCM, DGE	Canada	119	14 months	1 min	Household	HM	Gas, solar, other	No	Yes	13	N/A	52-60 (average)	✓			✓	✓			
35	Edwards et al. 2015	HWCM, HSD	Canada	73	2-5 months (Nov to Apr)	5 min	Household	HM	Solar	No	Yes	N/A	60	N/A	✓			✓				
36	Parker et al. 2015	HWCM	United States	69	1 year	1 year	Household	HM	Electricity, gas	No	Various	N/A	N/A	N/A								
	Chen et al. 2020	HWCM										N/A			✓							
37	Ahmed et al. 2016	HWCQ, HWCD	Finland	86	9-10 months (Apr to Jan)	1 h	Household	HM	District heating, solar	Yes	Yes	6	55	N/A	✓	✓		✓				
38	Makonin et al. 2016	DGE	Canada	1	2 years	1 min	Household	HM	Electricity, gas	No	No	N/A	N/A	N/A	✓	✓						
39	Binks et al. 2016	HWCM, RWEN	Australia	7	1 year	15 s	End use	N/A	Electricity, gas, solar	No	Various	16-18	N/A	35-65								
	Binks et al. 2017	RWEN		5												✓						
40	DeOreo et al. 2016	EUWC, WC	Canada, United States	94	2 weeks (various months)	10 s	End use	HM + DC	N/A	No	N/A	N/A	N/A	N/A	✓	✓				✓	✓	✓
	Chen et al. 2020	HWCM		94	2 weeks (various months)	10 s									✓					✓	✓	

	Vitter and Webber 2018	HWCM, DGE		95	2-3 weeks (various months)	7 s, 10 s																
	U.S. Environmental Protection Agency 2026	HWCQ		N/A	N/A	N/A															✓	
41	Verhaert et al. 2016	HWCQ, HSD	Belgium	20	N/A	1 s	Household	HM	Gas	No	Various	10	60	N/A								
42	Chmielewska et al. 2017	HWCD, HWCM	Poland	626	2 years	6 months	Household	HM	N/A	N/A	N/A	N/A	N/A	N/A	✓							
	Chmielewska et al. 2025	HWCM		1376	2-5 years	1 h, 1 month							55	N/A				✓	✓			
43	De Santiago et al. 2017	HWCM, RWEN	Switzerland	4	1 year	N/A	Household	HM	Electricity	No	Yes	10	60	N/A	✓			✓				
44	Aguirre et al. 2019	HWCM	Argentina	90	4 weeks	1 h	Household	HM	N/A	N/A	N/A	N/A	N/A	N/A								
45	Marszal-Pomianowska et al. 2019	HWCQ, DGE	Denmark	1	2 weeks (Dec)	2 Hz	End use	EM	N/A	No	N/A	N/A	N/A	Less than 55								✓
46	Zuniga-Alvarez et al. 2019	HSD	Canada	73	18 months (Nov-Apr)	5 min	Household	N/A	N/A	N/A	N/A	N/A	N/A	N/A								
47	Averfalk et al. 2021	HSD	Sweden	268	18 days (Oct-Nov)	15 min, 1 min, 6 seconds	Household group	AM	N/A	Yes	N/A	N/A	N/A	N/A								
48	Marszal-Pomianowska et al. 2021	HWCQ, DGE	Denmark	2	4-7 weeks (various months)	8 Hz	End use	EM	District heating, other	No	No	N/A	55	N/A	✓	✓		✓		✓	✓	✓
49	Lee and Yim 2021	HWCQ, HWCD	Korea	918	1 year	30 s	Household	HM	N/A	Yes	No	N/A	N/A	46-48								

50	Walnum et al. 2021	RDP	Norway	294	6 weeks (Jan to Mar)	2 s	Household group	AM	N/A	Yes	Yes	N/A	N/A	N/A										
	Sørensen et al. 2021	HWCQ, RWEN		1	50 days (Jan to Mar)																			
51	Arsene et al. 2022	DGE	N/A	N/A	N/A	1 min	End use	EM	N/A	N/A	N/A	N/A	N/A	N/A							✓		✓	
52	Sborz et al. 2022	HWCQ	Brazil	154	16 months	1 h	Household	HM	Electricity, solar	No	Yes	N/A	N/A	N/A	✓			✓	✓	✓	✓		✓	✓
	Sborz et al. 2024	HWCQ, HWCD		220	2 years		Household				-				✓	✓			✓	✓	✓			✓
53	Meireles et al. 2022	HWCQ, HWCM	Belgium	9181	3 years	1 month	Household	HM	N/A	N/A	N/A	N/A	N/A	N/A		✓					✓			
54	Canale et al. 2023	HWCQ, DGE	Poland	N/A	14 years	1 day	Household group	AM	District heating, other	Yes	Yes	N/A	N/A	41-45										
55	Salmanova and Yusupov 2023	HSD	Azerbaijian	1	N/A	N/A	Household	N/A	Solar, other	No	Yes	N/A	65	N/A	✓									
56	Department for Energy Security and Net Zero 2024	HWCQ	United Kingdom	5000	1 year	1 s	End use	HM + DC	Gas	No	No	N/A	55	48			✓					✓		
57	Mazzoni et al. 2025	HWCQ	Italy	5	3-5 months (Nov to Mar)	5 min	End use	EM	N/A	No	N/A	N/A	N/A	N/A	✓	✓		✓		✓	✓		✓	
58	Schattmann et al. 2025	RDP	Germany	N/A	N/A (four winter seasons)	1 min	Household group	AM	Gas	Yes	Yes	N/A	N/A	N/A										
59	Graupera Serra et al. 2026	RDP	Spain	10	1 year	7 min	Household	HM	N/A	N/A	N/A	N/A	N/A	N/A										

Note: [a] Study no longer accessible in the literature, data derived from Butler (1991); [b] Study no longer accessible in the literature, data derived from Parker et al. (2015) and Fuentes et al. (2018); [c] Study no longer accessible in the literature, data derived from Becker and Stogsdill (1990); [d] Study no longer accessible in the literature, data derived from Gleick et al. (2003); [e] Study no longer accessible in the literature, data derived from Chen et al. (2020); [f] Study no longer accessible in the literature, data derived from Parker et al. (2015) and Chen et al. (2020); AM = Aggregate-level monitoring (household groups); DC = (End-use) disaggregation and classification;

DGE = Data gathering and elaboration; EM = End-use-level monitoring (individual fixtures); EUWC = End-use water consumption analysis; HM = Household-level monitoring (individual households); HSD = Heating system design; HWCD = Hot-water consumption drivers; HWCM= Hot-water consumption modelling; HWCQ = Hot-water consumption quantification; I = Interaction with householders'; RDP = Raw data presentation; RWEN = Residential water-energy nexus; TM = Temperature-based inference approach; WC = Water conservation; WWQ = Wastewater quantification; N/A = Not available (i.e. unreported information).

Table 1. Overview of the 59 Hot-Water Databases (HWD) and the related 77 Residential Hot-Water Studies (RHWS) identified.

[See attachment]

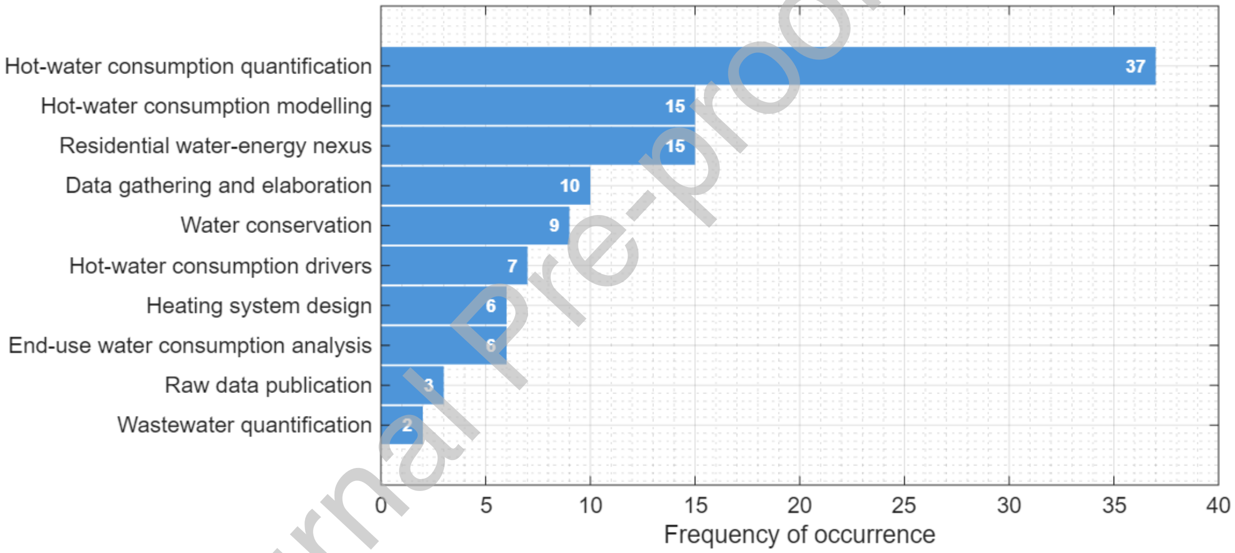


Figure 2. Aims of the 77 RHWSs reviewed.

2.2. Database characteristics

For each of the 59 HWDs, the review covers eight specific fields: (1) database location; (2) household sample size; (3) average duration of the monitoring period per household; (4) temporal resolution of monitoring; (5) aggregation level (i.e., household groups, individual households, or end uses of water); (6) approach adopted to obtain HWC data; (7) type of hot-water heating system; and (8) temperature monitoring.

The characteristics of each HWD are investigated exclusively based on the information reported in the related RHWS(s). This approach ensures methodological consistency, given that the vast majority of databases are not publicly accessible. Among the available open-access databases (i.e., HWDs used by Walnum et al., 2021; Arsene et al., 2022; Mazzoni et al., 2025; Schattmann et al., 2025; and Graupera Serra et al., 2026), many consist of raw data repositories with limited documentation or guidance for proper use, which often preclude further processing and interpretation. Moreover, most of the selected fields are consistent with those applied in previous reviews on water consumption across different aggregation levels (from urban to end-use scale), such as the works by Di Mauro et al. (2021) and Mazzoni et al. (2023b). In the present study, two additional fields specifically related to HWC characterization are introduced, namely the type of hot-water heating system and temperature monitoring. It should be noted that the study of HWD characteristics is limited to a preliminary classification of the datasets and their features, whereas specific levels of analysis are defined and applied in the subsequent phases of this study to extrapolate substantial information from the data.

HWD characteristics are summarized in **Table 1**. The following criteria are applied across different fields: (1) for household sample size and temporal resolution of monitoring, the largest sample size and finest resolution reported in the corresponding RHWS are considered, respectively. For example, in cases where the HWD includes measurements collected from varying numbers of households or at multiple temporal resolutions, the maximum sample size and the finest temporal resolution are used for classification; (2) for the method used to obtain HWC data and the type of hot-water heating system, all reported instances are considered to capture the full range of approaches and system configurations, providing a comprehensive overview of the analyzed studies.

The key findings of the preliminary analysis of HWDs are discussed in the following.

2.2.1. Location

Most HWDs were developed in North America (24) and Europe (24), with far fewer originating from other continents (**Figure 3**). This contrasts with the findings of Mazzoni et al. (2023b) on the residential end uses of water, in relation to which a substantial share of data also come from Oceania, a continent that is frequently affected by water scarcity and drought, and where detailed water-consumption characterization is often a priority for implementing water-management strategies.

Concerning North America, HWDs are distributed across diverse locations, ranging from warm and mild regions (Florida and North Carolina, United States) to cold regions (Ontario and Québec, Canada). In Europe, HWDs were primarily developed in central or northern countries, such as Belgium, Denmark , Poland, and Scandinavian countries, where energy requirements for water heating are particularly relevant due to cold winter temperatures and, more generally, the climatic regime. Conversely, fewer HWDs specifically developed for hot-water analysis are available for Mediterranean or Atlantic

European countries. Finally, two HWDs cannot be geographically identified, as the corresponding RHWSs were either unavailable in the literature or did not provide explicit information on their location (Thrasher and DeWerth, 1993; Arsene et al., 2022).

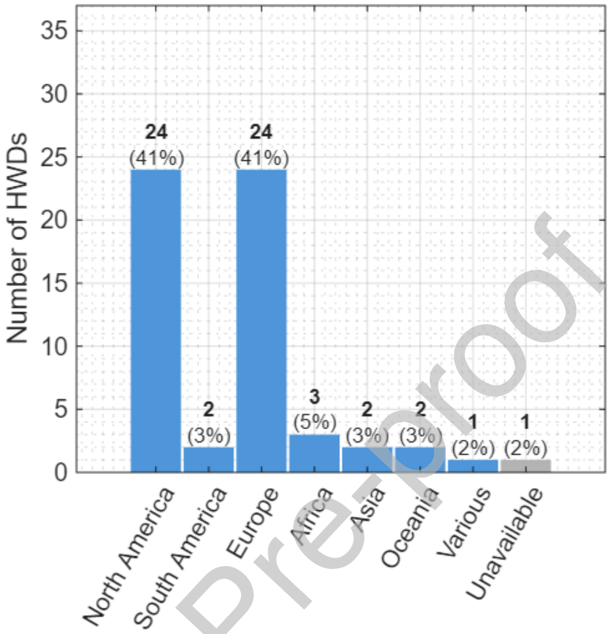


Figure 3. HWD characteristics: investigation by location.

2.2.2. Household sample size

A large number of analyzed HWDs are related to small and medium-sized household samples, comprising fewer than ten dwellings (14 HWDs) or tens of dwellings (23 HWDs). Conversely, only a minority of databases monitored larger household samples, with 9 HWDs covering more than 100 households and only 5 HWDs covering more than 1,000 households (**Figure 4**).

Consistent with the findings of the study on residential end uses of water by Mazzoni et al. (2023b), the analysis reveals that, in general, household sample size tends to decrease as the temporal resolution of HWC monitoring increases, reflecting the greater effort required to manage and process the larger volumes of data generated. For example, the HWD used by Meireles et al. (2022) includes data from over 9,000 households monitored at a monthly resolution. The same resolution was adopted in Gerin et al. (2014) and Chmielewska et al. (2025), which include more than 8,000 and 1,300 households, respectively. In these cases, monitoring at finer temporal resolutions was still performed, but only for a much smaller subset of households. Conversely, most HWDs with samples of ten or fewer households were developed based on high-resolution HWC monitoring, ranging from the minute scale (e.g., Weihl and Kempton, 1985; Makonin et al., 2016; Mazzoni et al., 2025) up to 10^0-10^1 hertz (e.g., Marszal-Pomianowska et al., 2019; 2021).

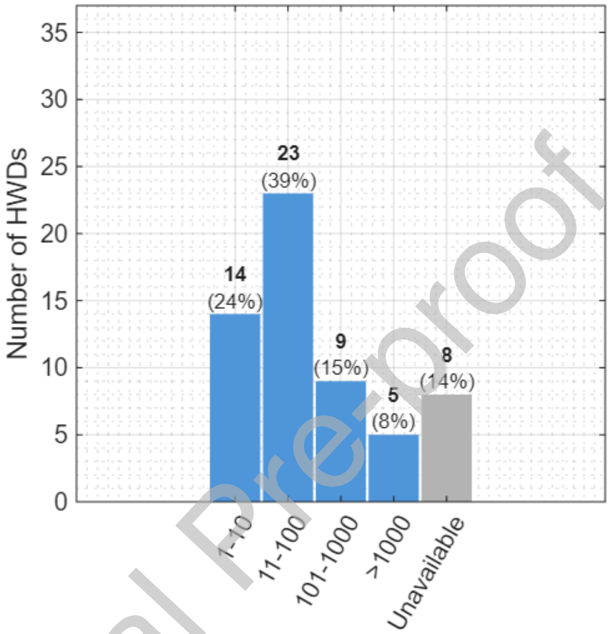


Figure 4. HWD characteristics: investigation by household sample size.

2.2.3. Average duration of the monitoring period

The majority of HWDs (i.e., 32 out of 59) include data from yearly monitoring periods, whereas a smaller number refers to shorter periods (**Figure 5**). This contrasts with other research on water consumption, e.g., studies on residential end uses of water, most of which involve more limited monitoring periods, e.g., only several weeks or a few months (Mazzoni et al., 2025). Despite these differences, a similar trend can be observed: the average monitoring duration generally decreases with increasing temporal resolution or with larger household sample sizes. For example, RHWSs aimed at investigating residential end uses of hot water (e.g., Mayer et al., 2000; 2003; DeOreo et al., 2016) featured sub-minute resolution data collected for only a few weeks per household. Conversely, HWDs with monitoring periods exceeding one year were typically developed for a very limited number of households (Lowenstein and Hiller, 1998; Schoenbauer et al., 2012; Binks et al., 2016), for groups of households such as multi-apartment buildings

(Bøhm, 2013), or at much coarser temporal resolutions (monthly or longer) (Parker et al., 2015; Meireles et al., 2022; Canale et al., 2023). A notable exception is the HWD developed by Lee and Yim (2021), which includes individual monitoring of nearly 1,000 households for more than one year with a 30-second resolution. Finally, it is important to note that sub-yearly monitoring periods can limit the ability to investigate seasonal variations in HWC. Indeed, studies explicitly addressing seasonal profiles typically rely on datasets covering at least one full year of monitoring.

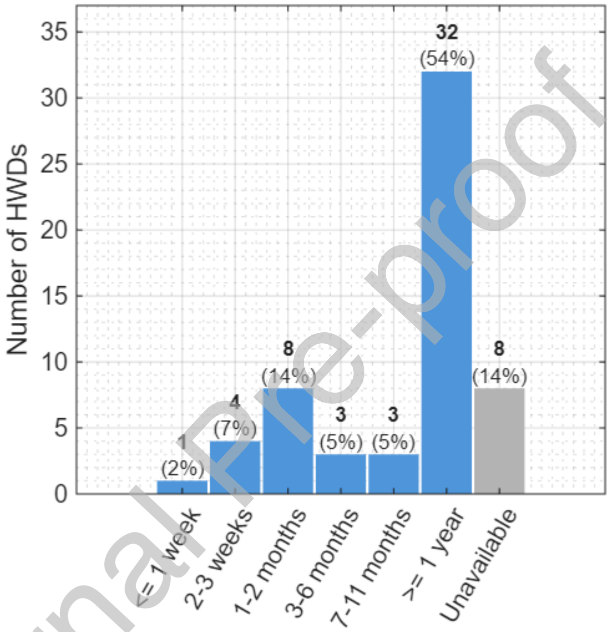


Figure 5. HWD characteristics: investigation by monitoring period duration (average per household).

2.2.4. Temporal resolution of monitoring

The reviewed HWDs exhibit a wide range of monitoring temporal resolutions, with no single category prevailing, as shown in **Figure 6**. Overall, most studies monitored HWC with fine sampling frequencies, from 1–5 minutes (15 HWDs) up to a few seconds (12 HWDs). Specifically, all studies aiming to investigate HWC at the individual end-use scale – either directly or indirectly – used HWDs featuring data with fine temporal resolutions, confirming that these are generally required to characterize end-use water consumption when direct monitoring is not feasible (e.g. through end-use disaggregation and classification methods) (Cominola et al., 2018; Heydari et al., 2022). Nevertheless, several studies focusing only on the quantification of HWC at higher aggregation levels, such as individual households or groups of households, also employ fine temporal resolution.

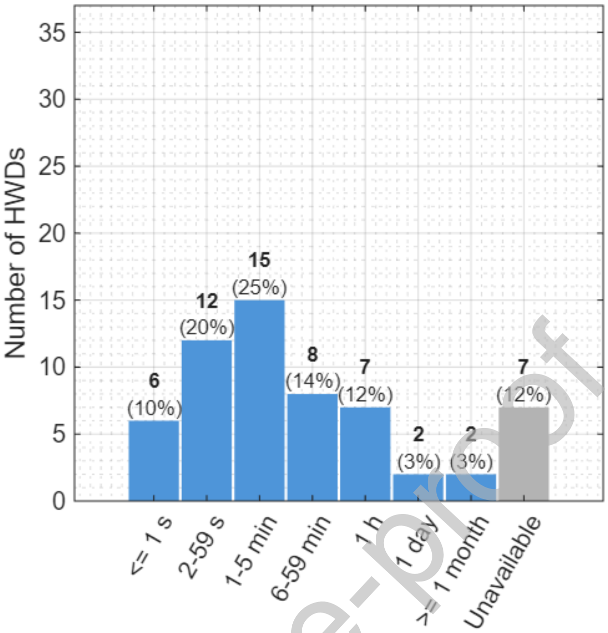


Figure 6. HWD characteristics: investigation by temporal resolution of monitoring.

2.2.5. Aggregation level

The review reveals that the aggregation level of each HWD is primarily related to the objectives of the corresponding RHWSs. In 30 cases, HWC data are provided at the scale of individual households or end uses of water, as shown in **Figure 7**. On the one hand, household-scale HWDs are typically employed in studies aiming to characterize hot-water use by reporting summary statistics – such as the average daily HWC per household or per person (e.g., George et al., 2015; Makonin et al., 2016; Meireles et al., 2022) –, household-scale daily profiles (e.g., Ahmed et al., 2016; De Santiago et al., 2017; Lee and Yim, 2021), or aggregate seasonal trends (e.g., Perlman and Mills., 1985; Chao et al., 2015; Chmielewska et al., 2025). On the other hand, 22 HWDs provide HWC data at the end-use scale, thus enabling the quantification of similar metrics for one (e.g., Sborz et al., 2022; 2024) or several (e.g., Abrams and Shedd, 1996; DeOreo et al., 2016) categories of domestic fixtures. In these cases, hot-water use is analyzed for a range of purposes, including water consumption modeling (e.g., Binks et al., 2016; Chen et al., 2020), the assessment of water-conservation potential through specific fixture-retrofitting interventions (e.g., Sullivan and Parker, 1999; Mayer et al., 2000; 2003), the bottom-up estimation of wastewater (e.g., Butler, 1991), and the development of data acquisition systems integrating multiple sensor types (e.g., Henze et al., 2002; Vitter and Webber, 2018; Marszal-Pomianowska et al., 2019). Conversely, only 7 HWDs include HWC data collected over groups of households – such as a single (Bagge and Johansson, 2011), a few (Milligan, 1987; Papakostas et al., 1995; Bøhm, 2013; Walnum et al., 2021), or even over 100 (Canale et al., 2023) multi-apartment buildings – without employing methods to disaggregate data to the scale of individual households or end uses. Additionally, the observed variety in data aggregation levels is closely linked to the approach adopted to obtain HWC data, which represents another key criterion considered in the preliminary investigation.

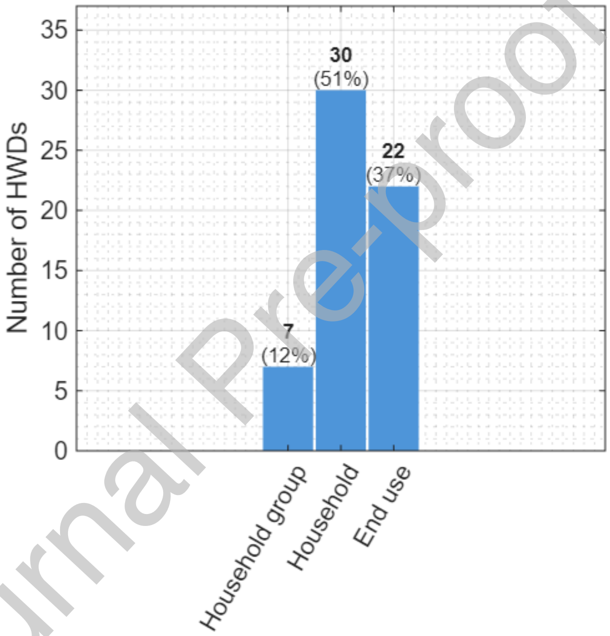


Figure 7. HWD characteristics: investigation by aggregation level.

2.2.6. Approach adopted to obtain HWC data

The most common technique used to investigate HWC is direct monitoring, typically involving the installation of a flow-rate sensor on the hot-water inlet pipeline supplying individual households (HM; **Figure 8**), multi-dwelling buildings, or even entire groups of buildings supplied by the same water-heating system (AM; **Figure 8**). It is worth noting that, depending on the objectives of the related RHWSs, an additional meter was often installed on the cold-water inlet to allow comparisons between hot- and cold-water consumption or to evaluate total household water use (Anderson et al., 1993; Gerin et al., 2014; Ahmed et al., 2015; Chao et al., 2015; Ahmed et al., 2016; Makonin et al., 2016;

Chmielewska et al., 2017). Direct monitoring also emerges as the most common approach for end-use scale investigations, involving separate HWC measurements at individual fixtures (EM; **Figure 8**).

However, beyond studies based on direct monitoring, several HWDs include hot-water measurements at the household scale (i.e., flow-rate monitoring at the household inlet) while deriving additional information on end uses – or groups of end uses – through various indirect methods. One example is the HWD developed by Sborz et al. (2022; 2024), which recorded household-scale HWC in a sample of 150–220 dwellings in Brazil, where showers represent the only hot-water fixtures; hence, end-use water consumption for this fixture category can be inferred solely from the household-scale HWC time series. Another example involves *temperature-based inference approaches* (TM; **Figure 8**), which rely on the principle that activating a fixture requiring hot water produces a measurable increase in the temperature of the corresponding branch of the plumbing system. Such approaches were adopted by Weihl and Kempton (1985), Abrams and Shedd (1996), and Lowenstein and Hiller (1998), who installed thermometers at specific points along the plumbing network, as well as by Henze et al. (2002), DEFRA (2008), and Schoenbauer et al. (2012), who extended temperature monitoring to individual fixtures. In other cases, information on hot-water use at the fixture scale was obtained through automated end-use disaggregation and classification techniques applied to high-frequency data (i.e., sampling intervals shorter than one minute) collected at the household inlet. In other cases, information on hot-water use at the fixture scale was obtained through automated end-use disaggregation and classification techniques (DC; **Figure 8)** applied to high-frequency data collected at the household inlet. Examples include the HWDs used in Thomas et al. (2011), Henderson and Wade (2014), and DeOreo et al. (2016), where HWC was disaggregated into individual end uses without explicit labeling, as well as Mayer et al. (2000; 2003) where hot-water uses were also classified using the TraceWizard® software. Additionally, Vine et al (1987) obtained HWC data through a hybrid approach combining hot-water measurements at the inlet of four multi-apartment buildings with thermal sensors installed at key points in the plumbing system and household surveys to estimate individual apartment consumption.

Overall, these examples highlight that, while direct monitoring remains the predominant approach, alternative data collection methods are sometimes adopted depending on contextual and technical constraints.

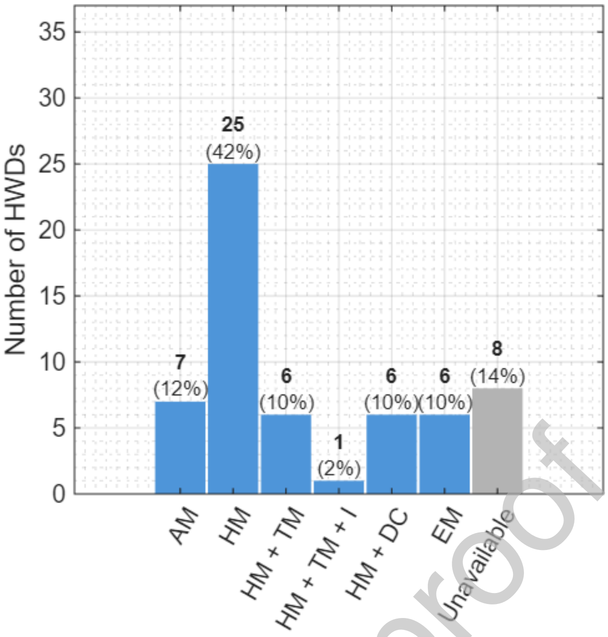


Figure 8. HWD characteristics: investigation by HWC data obtainment method. Note: AM = aggregate-scale monitoring (household groups); HM = household-scale monitoring (individual households); EM = end-use scale monitoring (individual fixtures); TM = temperature-based inference approach; DC = end-use disaggregation and classification methods; I = interaction with users.

2.2.7. Type of hot-water heating system

In general, the type of heating system can be characterized along three main dimensions: (1) heating technology and energy source (e.g., gas, electricity, solar), (2) the degree of system centralization (centralized *versus* decentralized systems), and (3) the presence or absence of a storage hot-water tank. However, as shown in **Table 1**, these aspects are generally poorly documented in relation to the reviewed HWDs.

Details on heating technology and energy source are available for only 31 of the reviewed HWDs, revealing a highly heterogeneous set of systems. Apart from a few studies focusing on a single water heating system type, most HWDs include households equipped with multiple system types. Among these, gas- and electricity-based heaters (both tank and tankless) appear most frequently, characterizing 15 and 13 HWDs, respectively. In addition to conventional heating systems, 14 HWDs include data from households equipped with solar-assisted systems, often integrated with *other* heating technologies such as gas or electric heaters, heat pumps (Merrigan, 1988; Papakostas et al., 1995; Knight et al., 2007; Henderson and Wade, 2014; Marszal-Pomianowska et al., 2021), desuperheaters (Merrigan, 1988), or wind (Salmanova and Yusupov, 2023). Other studies report hot-water monitoring in dwellings supplied by district heating systems, either in combination with recirculation systems (Bøhm, 2013; Canale et al., 2023), solar systems (Ahmed et al., 2015; 2016), or other hybrid configurations (Marszal-Pomianowska et al., 2021).

Information on system centralization is reported in relation to 47 HWDs, revealing that most HWDs are based on decentralized systems (29 HWDs), where hot water is produced at the dwelling-unit scale. In contrast, 9 HWDs refer to centralized hot-water production systems typically serving multiple dwellings and often including district-heating, while only 4 HWDs include a mix of centralized and decentralized configurations within the same household sample (Abrams and Shedd, 1996; Lowenstein and Hiller, 1998; Knight et al., 2007; CEC, 2008).

Finally, the availability of a hot-water storage tank is documented for 37 HWDs, 22 of which involve systems equipped with storage tanks, while 10 databases include both tank and tankless configurations, and only 5 account for tankless systems (**Figure 9**). Overall, the presence of a storage tank in the water-heating system is particularly relevant for HWC characterization, as monitoring performed upstream of the tank can distort the true actual profiles of HWC. However, based on the reviewed RHWSs, no studies specifically examine the extent to which tank storage alters HWC profiles, making this issue unexplored in the literature.

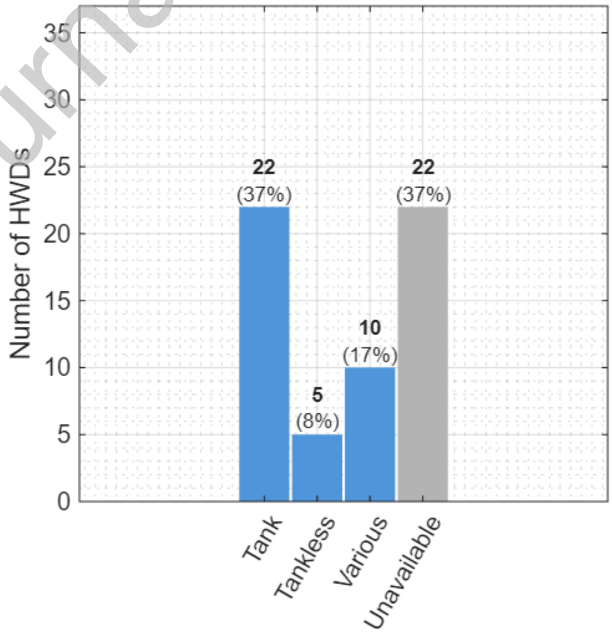


Figure 9. HWD characteristics: investigation by water-heating system type (tank presence).

2.2.8. Temperature monitoring

Temperature can be observed at different sections of the hot-water plumbing system: (1) upstream of the heating source (i.e., *inlet temperature*); (2) immediately downstream of the heating source (*outlet temperature*); and (3) at domestic fixtures (*end-use temperature*). The (positive) difference between outlet and inlet temperature is related to the thermal energy supplied by the heating system, whereas the (negative) difference between end-use and outlet temperature reflects heat losses along the domestic distribution system. Temperature data for at least one of these three sections are available in 35 HWDs, while no temperature-related information is reported for the remaining 24 HWDs (**Figure 10**), highlighting the challenges associated with standardizing HWC values and profiles reported in the literature.

Inlet temperature is a key determinant in predicting residential water-related energy (Bors et al., 2017). This parameter directly influences the energy demand associated with residential HWC, as lower inlet temperatures require a higher proportion of heated water to achieve the user-defined set-point water temperature (Chen et al., 2021). Inlet temperature is reported in 15 HWDs. The average values shown for each database (**Table 1**) indicate a range from a few degrees Celsius in cold climates, such as Scandinavian countries (Ahmed et al., 2015; 2016), to approximately 20 °C in mild-to-warm climates, such as Australia (Binks et al., 2016) or Florida (United States) (Masiello and Parker, 1992), with most reported average values falling within the 10–15 °C interval. Inlet temperature, however, is strongly affected by seasonality (Abrams and Shedd, 1996; DEFRA, 2008; Agudelo-Vera et al., 2020). For this reason, several RHWSs – despite not directly monitoring or reporting inlet temperature – provide monthly or seasonal profiles of ambient air temperature over the HWC monitoring period (Merrigan, 1988; Lee and Yim, 2021; Sborz et al., 2022; 2024; Meireles et al., 2022; Canale et al., 2023). This aspect is relevant from an energy perspective, as lower inlet temperatures lead to higher energy requirements for water heating (Blokker et al., 2013). However, while higher inlet temperatures would reduce the energy demand for water heating, technical guidelines (e.g., NIPH, 2016; CDC, 2017; Hellenic Ministry of Health, 2017) and regulatory frameworks (e.g., Dutch Ministry of Infrastructure and Water Management, 2004; Spanish Ministry of Health, 2012; Health and Safety Executive, 2013) typically assume or recommend cold-water (thus inlet) temperatures below 20–25°C to limit the risk of microbial growth in building water systems. This is consistent with studies indicating that proliferation of pathogens such as *Legionella* mainly occurs within the 25–45°C range

(European Centre for Disease Prevention and Control, 2017; World Health Organization, 2017).

Outlet temperature is the most frequently reported thermal variable, available in 24 HWDs. Hot-water set-point temperatures are typically kept constant throughout the year (DEFRA, 2008), and the reported values indicate that most databases adopt outlet temperatures above 55 °C, with only a limited number of studies reporting lower values. This is consistent with the commonly adopted requirement of maintaining outlet temperatures of at least 55 °C to reduce the risk of *Legionella* proliferation (Gavaldà et al., 2019; Rasheduzzaman et al., 2020), in line with evidence that this pathogen is significantly reduced at temperatures above 50 °C and is effectively inhibited above 60 °C (European Centre for Disease Prevention and Control, 2017; World Health Organization, 2017). In this context, maintaining water temperature at the heating system (i.e., at the storage tank, where present, and in the downstream sections of the plumbing system) at or above these values is recommended in several international and national guidelines (CEN, 2005; French Ministry of Health, 2005; NIPH, 2016; Swedish National Board of Housing, Building and Planning, 2015; CDC, 2017; Hellenic Ministry of Health, 2017; FIOH, 2018; ASHRAE, 2020) and is in some cases mandated by regulatory frameworks (Dutch Ministry of Infrastructure and Water Management, 2004; DVDW, 2004; Spanish Ministry of Health, 2012; Health and Safety Executive, 2013; Standards Australia/New Zealand, 2021a). Despite the relevance of the above thermal value, the absence of outlet temperature data in more than half of the reviewed HWDs highlights the inability to systematically analyse this variable, as well as to standardize reported HWC to a reference temperature. Moreover, owing to heat losses along the distribution system, outlet temperature can differ substantially from end-use temperature, and therefore does not accurately represent the actual water temperature at the point of use (Ivanko et al., 2022).

End-use temperature values are reported for at least one end-use category in 9 HWDs. Despite studies suggesting that the desired water temperature can remain relatively stable over time for specific end uses, such as showers (e.g., Jacobs et al., 2018), the reviewed HWDs reveal a wide range of end-use temperatures, spanning from slightly above 40 °C (Papakostas et al., 1995) to nearly 60 °C (Vine et al., 1987). In the latter case, the reported values clearly suggest mixing with cold water to achieve the desired temperature. It is worth noting that end-use temperature is generally not explicitly addressed in technical standards or regulatory frameworks, except for recommendations to limit hot water supplied to end uses to below 50 °C, typically through the use of mixing valves, to prevent scalding (ASHRAE, 2020; Standards Australia/New Zealand, 2021a). Overall, this variability in end-use temperature values can reasonably be attributed to differences in plumbing layouts and characteristics, heating system setpoints, and heat losses along the plumbing system.

Finally, temperature measurements at multiple points are reported by some HWDs. For example, both inlet and outlet temperatures are reported in 10 HWDs, while two databases (George et al., 2015; Binks et al., 2016) provide information on both inlet and end-use temperatures. However, none of the reviewed HWDs report outlet and end-use temperatures simultaneously, preventing a direct assessment of heat losses along the domestic hot-water distribution system.

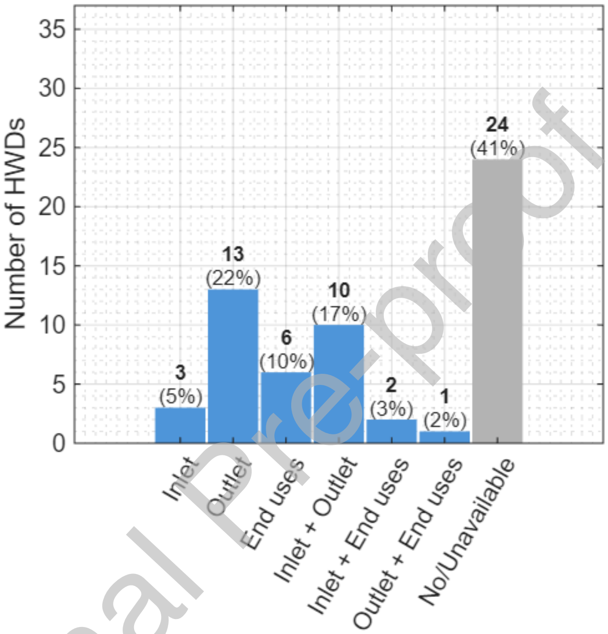


Figure 10. HWD characteristics: investigation by temperature monitoring point(s).

3. Methods

HWDs are examined through a multi-level framework aimed at comparing databases, deriving representative values, and identifying similarities and differences across studies. The following five aspects are investigated (**Figure 11**): (*Level 1*) daily per capita HWC; (*Level 2*) ratio of hot water to total water consumption (hereinafter referred to as the *hot-water ratio, HWR*); (*Level 3*) HWC parameter values (i.e., frequency, duration, volume, and flow rate of hot-water uses); (*Level 4*) HWC daily profiles; (*Level 5*) HWC monthly profiles.

The framework is inspired by the methodology proposed by Mazzoni et al. (2023b) and considers both the household and the end-use scales. Specifically, with respect to the end-use scale, the following categories of indoor fixtures potentially involving hot-water use are considered: *dishwasher* (D), *washing machine* (WM), *shower* (S), *bathtub* (B), and *taps* (T; i.e., kitchen sink and bathroom taps).

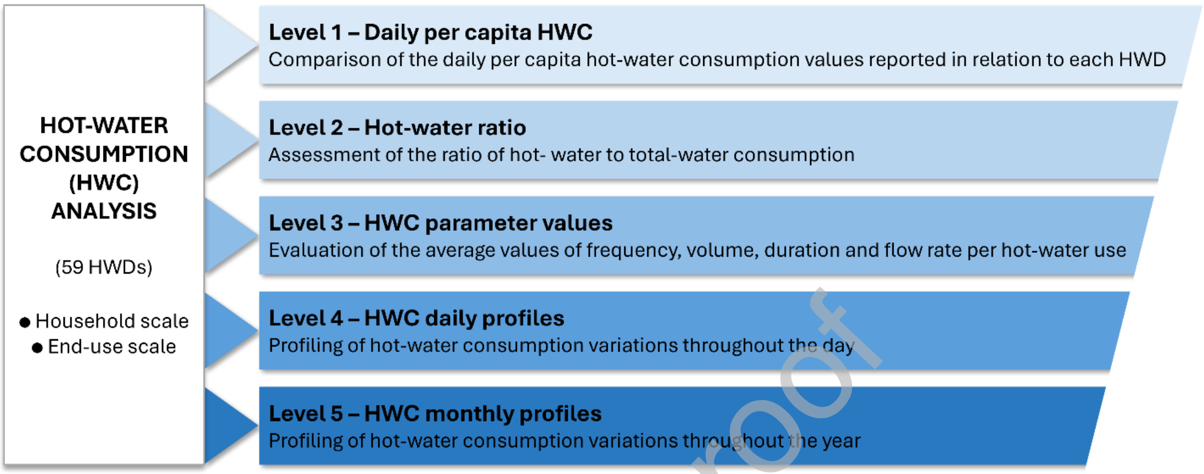


Figure 11. Method layout.

Although this method enables comparison of available data within a multi-level framework, the study is subject to challenges associated with to harmonizing information across databases, as discussed in the "*Study characteristics*" subsection. These challenges are primarily related to the differences in heating system configurations and output temperatures, which may lead to misrepresentations of actual HWC patterns and of temperatures at the point of use.

3.1. Level 1: daily per capita HWC

Daily per capita HWC (L/person/day) is used as a basic indicator to quantify the amount of residential hot water consumed on a daily basis. This parameter is derived for each HWD according to the aggregation level(s) adopted in the dataset. In studies directly reporting daily per capita average values of household- or end-use-scale HWC (L/person/day), the published data are used without further processing. However, when values are not directly available, a standardization process is carried out based on the following criteria.

- When daily per capita HWC (household or end-use scale) is expressed as a percentage of daily total water consumption, the corresponding value (L/person/day) is obtained by multiplying the percentage by the reported total consumption.

- When values are reported per household rather than per capita, the occupancy rate (persons/household), if available, is used to convert the values to L/person/day.
- When specific subsets of the sample (e.g., household types or family groups) are presented separately, a single representative value is calculated using a weighted average based on the size of each subset.
- When separate seasonal values are provided (e.g., cold and warm season), these are averaged to derive a yearly, seasonally-independent estimate.
- When studies report values before and after fixture retrofitting (e.g., installation of low-flow showerheads or taps, as in Mayer et al., 2000; 2003), the two scenarios are averaged for the comparative analysis. Nevertheless, pre- and post-retrofit values are individually retained in **Table 1** allowing for the assessment of water conservation measures impact.
- When a HWD includes data from heterogeneous geographic locations (e.g., multiple countries) reported separately rather than averaged, each location is treated separately to avoid averaging across substantially different contexts.
- At the end-use scale, when values are reported for aggregated fixture groups comprising multiple categories (e.g., showers and bathtubs combined, Kempton, 1988; Schoenbauer et al., 2012), they are excluded from the comparative analysis.

Finally, for all standardized daily per capita HWC values – at both household and end-use scales – the mean and standard deviation across all HWDs are calculated to derive an overall reference estimate.

3.2. Level 2: Hot-water ratio (HWR)

Assessing the proportion of hot water in relation to the total amount of water used (i.e., both hot and cold) provides additional insights into residential water-use behaviours at the household or end-use scales. To this end, HWR (%) is introduced to express this proportion as a percentage. When not explicitly reported, HWR is derived from a household- or end-use-scale water balance, where possible. Specifically, this information is inferred from the availability of cold-water consumption data alongside the hot-water data, as detailed in the *2.2.6. Approach adopted to obtain HWC data* subsection.

As for Level 1 of the analysis, mean and standard deviation across HWDs are computed for both household- and end-use-scale HWR to obtain an overall reference estimate.

3.3. Level 3: HWC parameter values

In addition to average HWC and HWR, the characteristics of individual hot-water uses are also examined. In line with the approach introduced by Mazzoni et al. (2023b), three parameters are investigated, at either the household level or for a specific end-use category: (1) daily per capita frequency of use (uses/person/day); (2) average volume per use (L/use); and (3) average duration per use (min/use) . From an operational standpoint, the same standardization criteria adopted for Level 1 are applied to ensure comparability of these parameters across HWDs, after which mean and standard deviation are computed for all datasets where such information is available. In addition, parameter values are excluded from the comparative end-use analysis when reported in incompatible formats, e.g., appliance parameters expressed in terms of single water withdrawals rather than full operational cycles (*loads*) (Kempton, 1988; Henderson and Wade, 2014), or end-use parameters provided only for a subset of a category (e.g., kitchen taps but not bathroom taps, as in Marszal-Pomianowska et al., 2019).

3.4. Level 4: HWC daily profiles

Level 4 of the analysis examines daily HWC profiles reported in the RHWSs, with the aim of understanding how hot water is used throughout the day, identifying peak periods, and assessing similarities and differences relative to total water-consumption profiles. However, daily hot-water profiles are mainly presented in the literature in graphical form and through heterogeneous formats (e.g., hourly percentages of the daily total, or hourly volumes). Due to this predominance of graphical data, all profiles are digitized using the *Web Plot Digitizer v5* software (Rohatgi, 2024). Additionally, to enable comparison across studies, the digitized profiles are aggregated at the hourly resolution (if not directly available) and normalized with respect to the 24-hour average value, yielding a set of 24 hourly dimensionless coefficients that assume values greater than 1 during hours when HWC exceeds the daily average and values below 1 during hours with lower-than-average use.

Daily HWC profiles are obtained for each HWD by applying the following assumptions: (1) household- (or end-use profiles) derived from HWDs monitoring only a single household (or a single end use) and based on fewer than three days of observation are excluded from the analysis; (2) for HWDs reporting profiles only for different seasons (e.g., cold and warm season), an average profile is first computed to obtain a representation not influenced by seasonal variability, although the individual seasonal profiles are retained for subsequent comparison; and (3) for HWDs presenting separate weekday and weekend (or holiday) profiles, a weighted average is calculated to derive a result not affected by day type, while individual weekday and weekend/holiday profiles are retained for comparative analyses.

3.5. Level 5: HWC monthly profiles

Level 5 of the analysis focuses on the assessment of seasonal trends made possible by the large number of HWDs reporting HWC over monitoring periods of at least, or exceeding, one year. As with daily profiles, the available seasonal trends – typically presented in graphical form at monthly resolution or obtained by aggregating sub-monthly data – are digitized using *Web Plot Digitizer* v5 (Rohatgi, 2024) and subsequently normalized with respect to the annual average, yielding twelve monthly coefficients that reflect deviations above or below the yearly mean. To ensure consistency across studies, all normalized profiles are standardized to the temporal reference of the Northern Hemisphere: specifically, profiles from studies conducted in the Southern Hemisphere are aligned to the seasonal cycle of the northern one.

4. Results and Discussion

Given the large amount of information reported in the literature for the different levels of the analysis, a preliminary assessment is carried out to identify which aspects of HWC are most frequently available in the reviewed HWDs. In greater detail, information concerning the availability of results for each level of the analysis is reported in **Table 1** for each HWD and RHWS. An overview of data availability for every level of analysis is also depicted in **Figure 12**, with the label "*Unavailable*" indicating HWD features that could not be assessed referring to the studies available in the literature.

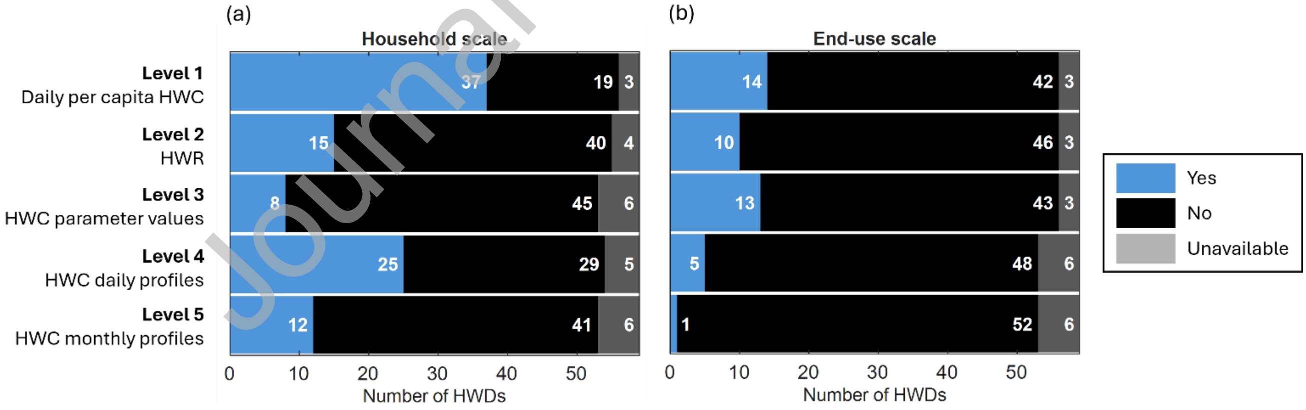


Figure 12. Number of HWDs providing results related to each level of the analysis.

Overall, the findings highlight a clear predominance of household-scale data in the literature (**Figure 12a**), with a strong emphasis on daily consumption and profiles. At the household scale, daily per capita HWC (Level 1) emerges as the most consistently reported metric, followed by daily HWC profiles (Level 4), whereas the reporting of HWR

(Level 2), HWC parameters (Level 3), and monthly profiles (Level 5) is markedly less common. The predominance of information on household-scale daily averages and profiles likely reflects their primary role as input parameters for most applications in HWC modelling (Parker et al., 2015; Vitter and Webber, 2018; Chmielewska et al., 2017), heating system design (Knight et al., 2007; Edwards et al., 2015; Verhaert et al., 2016), or investigations of the domestic water–energy nexus (CEC, 2008; Bøhm, 2013; De Santiago et al., 2017), whereas hot-water use parameters and HWRs are typically available in RHWSs with different purposes, e.g., data gathering and elaboration (Henze et al., 2002; Makonin et al., 2016) or the application of water conservation strategies (Chao et al., 2015).

As opposed to the household scale, end-use-scale information on HWC is much more limited (**Figure 12b**). At this aggregation level, daily per capita HWC (Level 1) remains the most frequently reported metric, followed by hot-water use parameters (Level 3) and HWR. In contrast, daily or monthly profiles for individual end uses (Levels 4 and 5) are almost entirely absent from the literature. The greater availability – beyond average values – of HWR and HWC parameter values largely reflects the specific focus of the reviewed studies on end uses. Among these, some RHWSs aim to characterize individual fixtures in terms of hot- and cold-water use, including the relative contribution of hot water, sometimes accompanied by details on the parameters characterizing individual end uses of water (Edwards et al., 1995; Mayer et al., 2000; Mayer et al., 2003; DeOreo et al., 2016; Mazzoni et al., 2025). Other studies primarily focus on the development of data collection systems with high temporal resolution and low aggregation level (Marszal-Pomianowska et al., 2019; 2021), which still allows obtainment of detailed parameter values based on the analysis of the collected HWC time series.

4.1. First level: daily per capita HWC

Daily per capita HWC values at the household scale are identified for 37 HWDs. The corresponding average values, along with available information on household occupancy, are reported in **Table 2**. It is worthy of note that, for 9 additional HWDs (not indicated in **Table 2**), daily per household HWC are available in the literature. However, due to the absence of data on average occupancy rates for the monitored samples, it was not possible to derive the respective daily per capita estimates. The related daily per household HWC values are included in the **Supplementary Materials** (**Table S1**).

Table 2. Daily per capita HWC data reported in relation to different HWDs.

HWD	**RHWS**	**Household sample (households)**	**Occupancy rate (persons / household)**	**Daily per capita HWC (L/person/day)**					
				Household	**DW**	**WM**	**S**	**B**	**T**
1	Butler 1991	-	3.2	53.4	-	-	-	14.7	38.7
2	Perlman and Mills 1985	55	3.8	62.1	-	-	-	-	-
4	Weihl and Kempton 1986 (*data from* Kempton 1988)	7	3.7	71.6	-	13.7	-	-	24.0
5	Vine et al. 1987	48	2.6	108.1	-	-	-	-	-
7	Merrigan 1988	98	3.6	62.4	-	-	-	-	-
9	Anderson et al. 1993 (pre-retrofitting)	25	2.9	59.8	-	-	-	-	-
	Anderson et al. 1993 (post-retrofitting)	25	2.9	50.3					
11	Meyer and Tshimankinda 1996	90	6.7	5.6	-	-	-	-	-
12	Papakostas et al. 1995	83	4.0	32.2	-	-	-	-	-
13	Abrams and Shedd 1996	27	2.4	70.1	-	-	-	-	-
14	Lowenstein and Hiller 1998	14	3.7	57.3	6.5	7.7	25.2	4.8	-
15	Meyer and Tshimankinda 1998a	90	3.1	55.7	-	-	-	-	-
16	Meyer and Tshimankinda 1998b	90	3.0	72.3	-	-	-	-	-
18	Jordan and Vajen 2001	-	2.0	100.0	-	-	40.0	10.0	14.0
19	Mayer et al. 2000 (pre-retrofitting)	10	2.6	94.6	3.4	14.8	23.8	15.9	32.6
	Mayer et al. 2000 (post-retrofitting)	10	2.8	77.6	3.8	5.7	26.5	9.5	29.1
20	Henze et al. 2002	1	2.0	113.7	1.5	30.0	35.1	0.6	43.0
21	Mayer et al. 2003 (pre-retrofitting)	10	2.5	79.9	5.3	7.2	26.1	6.4	32.6
	Mayer et al. 2003 (post-retrofitting)	10	2.5	62.4	3.8	3.8	22.7	5.7	23.5
22	Knight et al. 2007 (Canada)	-	2.9	94.0	-	-	-	-	-
	Knight et al. 2007 (United States)	-	5.7	40.0	-	-	-	-	-
	Knight et al. 2007 (Switzerland)	-	-	55.0	-	-	-	-	-
	Knight et al. 2007 (Finland)	-	2.2	43.0	-	-	-	-	-
	Knight et al. 2007 (United Kingdom)	-	1.7	29.5	-	-	-	-	-
	Knight et al. 2007 (Germany)	-	-	64.0	-	-	-	-	-
23	CEC 2008	41	2.7	86.8	-	-	-	-	-
24	DEFRA 2008	124	2.9	41.9	-	1.1	-	14.1	13.3
26	Thomas et al. 2011	74	3.3	56.2	-	-	-	-	-
28	Schoenbauer et al. 2012	10	2.7	53.0	2.1	3.7	-	-	14.3
31	Henderson and Wade 2014	5	2.6	91.7	6.1	7.6	55.6	-	22
32	Ahmed et al. 2015	182	2.1	43.0	-	-	-	-	-
33	Chao et al. 2015	59	2.6	51.0	-	-	-	-	-
34	George et al. 2015	119	3.8	44.9	-	-	-	-	-
35	Edwards et al. 2015	73	3.2	59.4	-	-	-	-	-
36	Parker et al. 2015	69	3.0	64.0	-	-	-	-	-
37	Ahmed et al. 2016	86	2.2	42.8	-	-	-	-	-
38	Makonin et al. 2016	1	3.0	60.3	-	-	-	-	-
40	DeOreo et al. 2016	94	2.2	79.1	3.8	7.6	30.6	4.5	26.5
42	Chmielewska et al. 2017	78	2.2	81.0	-	-	-	-	-
43	De Santiago et al. 2017	4	3.3	35.3	-	-	-	-	-
44	Aguirre et al. 2019	90	2.3	90.0	-	-	-	-	-

48	Marszal-Pomianowska et al. 2021	2	3.0	22.1	0.0	0.0	17.9	-	4.2
52	Sborz et al. 2024	220	3.0	32.5	0.0	0.0	32.5	-	0.0
55	Salmanova and Yusupov 2023	1	4.5	52.2	-	-	-	-	-
57	Mazzoni et al. 2025	5	2	33.9	0.0	0.0	-	-	26.0
	Average	**-**	**-**	**60.1**	**2.6**	**6.7**	**31.8**	**8.4**	**21.9**
	Standard deviation	**-**	**-**	**23.6**	**2.5**	**8.3**	**11.1**	**5.2**	**12.5**

Note: DW = dishwasher; WM = washing machine; S = shower; B = bathtub; T = taps.

Across the 37 HWDs for which daily per capita data could be derived, the resulting average daily HWC amounts to 60.1 L/person/day, with a standard deviation of 23.6 L/person/day. A statistical representation of the HWC averages referred to individual HWDs is shown in **Figure 13a**. The box–whisker plot reveals an overall symmetric distribution, with a median value of 56.8 L/person/day falling close to the mean, and quartiles and whiskers that are approximately balanced around it. It is worth noting that, when only the 17 HWDs with monitoring periods of at least one full year are considered to exclude potential biases induced by seasonal monitoring, the average daily HWC decreases to 51.6 L/person/day, with a standard deviation of 19.7 L/person/day. This reduction is likely attributable to the fact that most studies based on monitoring over limited periods, were conducted during the cold season, when HWC is expected to exceed the average.

Comparison with the reference values reported in (or derivable from) technical standards and guidelines – most of which provide aggregated total water consumption values (i.e., hot and cold water combined), while only a minority (listed in **Table S2** of the **Supplementary Materials**) allow HWC to be derived separately – shows generally consistent daily per capita HWC values, despite spanning very wide ranges. For example, European technical standards based on building energy models of domestic HWC indicate values of 20–50 L/person/day (CEN, 2017), with national energy-model-based ranges of 30–60 L/person/day in Germany (DIN, 2011; DIN, 2012) and 25–60 L/person/day in Italy (UNI, 2019), as well as design practice values of 22–30 L/person/day assumed in Spain (Spanish Ministry of Transport, Mobility and Urban Agenda, 2013; UNE, 2015). In Australia and New Zealand, HWC values used as inputs in energy models range from 45 to 60 L/person/day (Standards Australia/Standards New Zealand, 2021b), while values of 40–70 L/person/day are assumed for similar purposes in Canada (NRCan, 2025). Higher values, ranging from 50 to 200 L/person/day, are reported in the United States (ASHRAE, 2019), derived from end-use models with specific occupancy and simultaneity assumptions. It is worth noting that most values reported in technical standards and guidelines are energy-based and normalized to end-use temperatures (thus including a fraction of cold water), and therefore do not align with the study's focus on direct, field-based volumetric monitoring of HWC. Consequently, these standards are not classified as HWDs.

As for the temporal evolution of daily per capita HWC, **Figure 13b** shows average values from individual RHWSs plotted against their publication year, with marker sizes scaled to the monitored household sample size. Overall, dispersion in HWC values is observed – likely reflecting differences in sample size, location (and associated cultural habits), and inlet/outlet water temperatures – precluding a formal quantification of long-term variations due to these numerous sources of uncertainty. Nevertheless, some RHWSs across North America (Thomas et al., 2011; Edwards et al., 2015; George et al., 2015; Chen et al., 2020) and Europe (Ahmed et al., 2016) report a general long-term decrease in HWC. The literature attributes this reduction to multiple drivers, including technological, behavioral, economic, and regulatory factors (Meireles et al., 2022). On the technological side, because in some contexts dishwashers and washing machines are directly supplied with hot water (Marszal-Pomianowska et al., 2021), the diffusion of more efficient appliances has markedly reduced the total water consumption – and consequently the HWC – associated with these end uses (Edwards et al., 2015; Parker et al., 2015). Additionally, the widespread adoption of high-efficiency fixtures, such as low-flow showerheads and aerated taps, has contributed to lowering HWC for personal hygiene and general tapping (i.e. water use from washbasins and kitchen sinks) (Chen et al., 2020). Complementary behavioral and regulatory dynamics – such as shorter showers, lower-temperature laundry cycles, reduced hot water waste, rising water and energy prices, targeted campaigns, and stricter efficiency regulations – have further contributed to this trend (Mayer et al., 2003; Chen et al., 2020; Meireles et al., 2022).

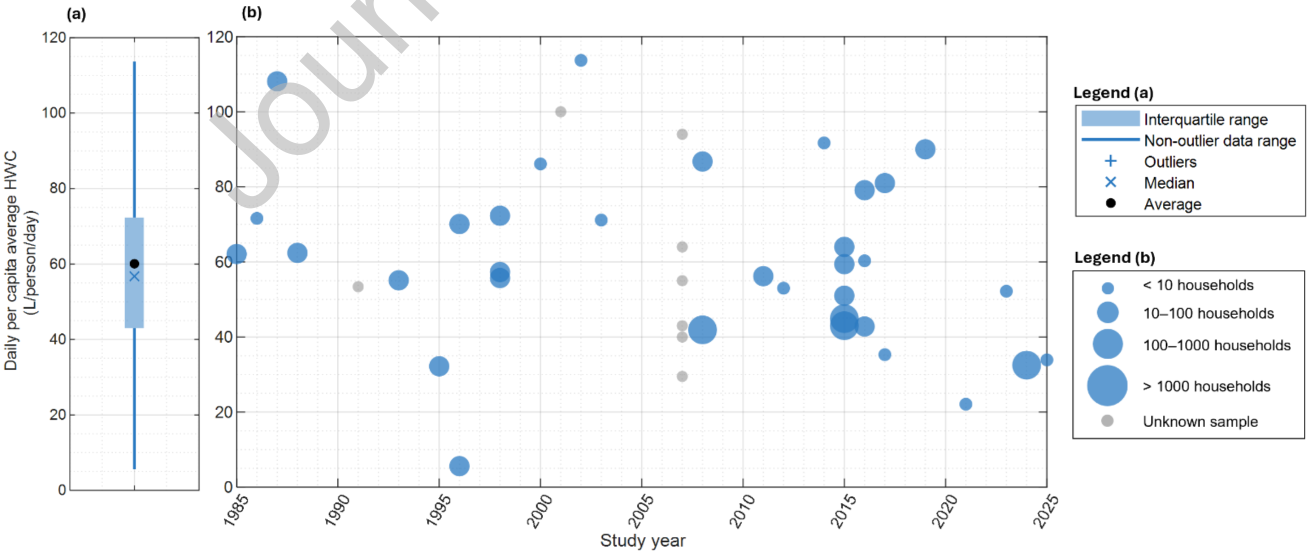


Figure 13. Daily per capita HWC at the household scale: (a) box-whisker plot of the average values reported in reviewed HWDs; (b) values reported in relation to the period 1985–2025.

Regarding the spatial distribution of daily per capita HWC, the preliminary analysis shows that the vast majority of available data originate from North America and Europe, limiting the possibility of a robust global comparison due to the scarcity of information available for other continents. Nevertheless, a comparison among the most represented regions highlights differences in daily per capita HWC, with North America showing the highest average value (around 71 L/person/day), and Europe the lowest (approximately 48 L/person/day). However, North American datasets are generally older, with an average study year of 2002, whereas European studies are more recent, averaging 2011. Within Europe, further differences emerge between Northern and Southern countries. Northern Europe (including data from Switzerland, Germany, Belgium, Denmark, Poland, Sweden, Norway, Finland, and the UK) shows an average HWC of about 51 L/person/day (average study year: 2010), while Southern Europe (Italy and Greece) exhibits a lower average of 33 L/person/day (average study year: 2010). This difference is likely primarily driven by climatic conditions, suggesting that daily per capita HWC is influenced not only by socio-economic and technological factors, but also by regional climate regimes.

At the scale of individual end uses, the results reported in the reviewed RHWSs (covering 14 HWDs) indicate that showers constitute the category with the highest HWC (31.8 L/person/day), followed by taps (21.9 L/person/day (**Table 2**, **Figure 14**). A broader spread characterizes tap-related values, suggesting greater heterogeneity in how hot water is used for general tapping across different contexts. In contrast, the distribution of shower-related values is more compact, reflecting the relatively consistent reliance on hot water for personal hygiene. Overall, the hot-water values obtained for showers and taps are lower than the corresponding total (hot- and cold-water) values reported by Mazzoni et al. (2023b), i.e., approximately 44 L/person/day for showers and 33 L/person/day for taps. This indicates that these end uses commonly rely on mixed water rather than predominantly hot water (Parker et al., 2015; Vitter and Webber, 2018), as also discussed in the *Second level: hot-water ratio* subsection. This interpretation is further supported by the findings of Marszal-Pomianowska et al. (2021), whose study shows that, at the point of use, hot water is generally mixed with cold water for hygiene-related activities.

As far as the other end-use categories are concerned, an average HWC of approximately 8.4 L/person/day is associated with bathtubs. This value is considerably lower than those observed for showers and taps, and confirms the long-term reduction in the use of bathtubs in favor of showering, as documented in multiple RHWSs (Butler, 1991; Mayer et al., 2000; 2003; DeOreo et al., 2016; De Santiago et al., 2017; Vitter and Webber, 2018).

In addition, a non-negligible share of HWC is associated with washing machines (6.7 L/person/day) and dishwashers (2.6 L/person/day), when these appliances are supplied directly by the hot-water line. The use of hot water in these appliances is a recurring theme across the analyzed studies. By comparing Danish and North American practices, Marszal-Pomianowska et al. (2021) argue that the higher HWC recorded in the United States and Canada for dishwashers and washing machines may be partly attributable to the common connection to the domestic hot-water plumbing system. Evidence from earlier RHWSs supports this interpretation: in the studies by Mayer et al. (2000, 2003), dishwasher use consisted entirely of hot water, whereas approximately 28% of washing-machine water consumption was hot, predominantly during the wash cycle (with rinse and spin cycles relying almost exclusively on cold water). Additional confirmation is provided by Parker et al. (2015), who estimate that 13–38% of the water used by American clothes washers is hot; for dishwashers, the same study reports that cold water supply occurs only in a very limited subset of the monitored households. Conversely, several authors note that such appliances are typically not connected to the domestic hot-water plumbing systems in Europe (Marszal-Pomianowska et al., 2021; Meireles et al., 2022). It should be emphasized, however, that the total hot-water balance associated with these appliances should also include the volume of water heated internally, for which none of the HWDs analyzed in this study provide information. Based on the limited data available in the literature (e.g., Blokker et al., 2013), a conservative approximations suggest an additional 10 L/person/day of cold water internally heated in washing machines and approximately 2 L/person/day in dishwashers. Overall, the differences between North American and European installation practices – together with the lack of rigorous studies comparing the energy efficiency of hot- *versus* cold-water appliance connections and the limited data on volumes of cold water heated internally within appliances – suggest that the characterization of HWC and the determination of the optimal supply strategy for these devices remain open questions.

The available results also provide insight into the effects of fixture-retrofitting campaigns on HWC. Anderson et al. (1993) report a reduction of approximately 16% (from 59.8 to 50.3 L/person/day) following the installation of efficient fixtures. Comparable reductions, on the order of 15–20%, are shown by Mayer et al. (2000; 2003), where the overall domestic HWC decreased from 94.6 to 77.6 L/person/day and from 79.9 to 62.4 L/person/day, respectively, following the replacement of conventional fixtures with water-efficient appliances. These studies also highlight effects on end uses: in Mayer et al. (2000), most end-use categories show reductions in HWC, in some cases exceeding 60%, with the exception of dishwashers and showers, where slight increases are observed due to longer usage durations. Overall, the results indicate that retrofitting campaigns and the introduction of efficient fixtures and appliances can contribute to lowering not only total water consumption but also the related hot-water fraction.

Finally, it is worth noting that the sum of HWC values reported in **Table 2** for end-use categories does not always match the total household HWC. This discrepancy arises primarily for two reasons. On the one hand, not all end-use categories are consistently monitored; for example, when appliances such as dishwasher or washing machines are connected to the hot-water line but lack dedicated monitoring, it is impossible to fully close the household-scale HWC balance (e.g., Kempton, 1988; Lowenstein and Hiller, 1998; Jordan and Vajen, 2001; DEFRA, 2008; Schoenbauer et al., 2012; Mazzoni et al., 2025). Second, end-use categories beyond those considered in this paper are sometimes reported, typically under the label “Other” (Mayer et al., 2000; 2003; DeOreo et al., 2016). In addition to the “Other” category, hot-water leakages are sometimes reported. For example, Mayer et al. (2000) show an average of 3.8 L/person/day of hot-water leakage in 10 houses in Seattle, while about 2.6 L/person/day of hot-water leakages were observed in 10 houses in the San Francisco Bay Area (Mayer et al., 2003). Similarly, DeOreo et al. (2016) report leakage values up to 7.8 L/person/day across more than 90 houses in the United States and Canada.

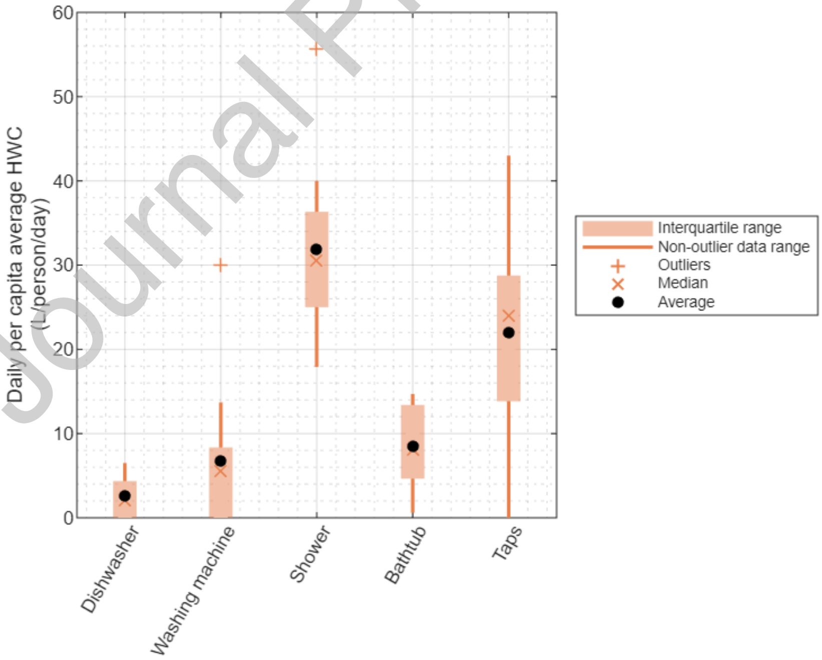


Figure 14. Daily per capita HWC at the end-use scale: box-whisker plots of the values reported in reviewed HWDs.

4.2. Second level: hot-water ratio (HWR)

HWR – expressed as the share of HWC over total residential water consumption – is less explored in the reviewed RHWSs (**Table 3**). At the household scale, values are available for 15 HWDs, yielding an average HWR of 35.3% and revealing that, on average, about one-third of residential water consumption is associated with hot-water use. The dispersion around the mean is limited, with a standard deviation of 9.4%. Nevertheless, HWR values span from less than 20% in the Brazilian context documented by Sborz et al. (2024), where mild climatic conditions allows the restrict of HWC essentially to showering, to nearly 60% in Denmark (Marszal-Pomianowska et al., 2021), where the more extensive HWR can be reasonably related to lower temperatures throughout the year.

At the end-use scale, 10 HWDs provide information on HWRs for at least one end-use category. Overall, the most documented fixtures are appliances (9 HWDs report HWR values for washing machines and 8 for dishwashers) and taps (8 HWDs), while fewer values are reported for showers and bathtubs (4 HWDs each). Despite the lower number of observations, showers and bathtubs are associated with the highest HWR values (with average ratios of 69.5% and 71.6%, respectively), followed by taps (54.0%). These results highlight that end uses associated with personal hygiene and cleaning activities consistently rely on hot water for more than half of their total water consumption. On the other hand, markedly heterogeneous values emerge for appliances, reflecting substantial differences across the reviewed RHWSs. As discussed in Section 4.1 and documented in the literature (Parker et al., 2015; Meireles et al., 2022), washing machines and dishwashers show markedly heterogeneous HWRs across RHWSs, reflecting differences in connection to cold or hot water. In some cases, appliances are supplied exclusively with cold water, resulting in nil HWRs (Marszal-Pomianowska et al., 2021; Mazzoni et al., 2025), while in others they are connected entirely to domestic hot water (Mayer et al., 2000; 2003; DeOreo et al., 2016). Consequently, average HWRs differ across RHWSs, with dishwashers showing a mean of 37.5% and washing machines 8.8%, both with high variability. For dishwashers, reported HWR values are typically 0% or 100%, indicating uniform supply configurations within each RHWS.

Table 3. HWR: average values reported in relation to different HWDs.

HWD	RHWS	Household scale (%)	End-use scale (%)				
			DW	WM	S	B	T
9	Anderson et al. 1993 (pre-retrofitting)	31.2	-	-	-	-	-
	Anderson et al. 1993 (post-retrofitting)	31.1	-	-	-	-	-
10	Edwards and Martin 1995	23.0	0.0	4.5	-	65.8	68.0
17	Gleick et al. 2003	-	-	20.7	-	-	-
19	Mayer et al. 2000 (pre-retrofitting)	40.0	100.0	27.8	73.1	78.2	72.7
	Mayer et al. 2000 (post-retrofitting)	49.2	100.0	15.1	75.5	80.5	79.5
21	Mayer et al. 2003 (pre-retrofitting)	29.8	100.0	15.3	71.9	89.5	65.2

	Mayer et al. 2003 (post-retrofitting)	29.6	100.0	10.1	60.0	75.0	50.0
30	Gerin et al. 2014	36.4	-	-	-	-	-
32	Ahmed et al. 2015	39.0	-	-	-	-	-
33	Chao et al. 2015	32.5	-	-	-	-	-
37	Ahmed et al. 2016	32.0	-	-	-	-	-
38	Makonin et al. 2016	48.0	-	-	-	-	-
39	Binks et al. 2017	40.7	-	-	-	-	-
40	DeOreo et al. 2016	33.2	100.0	20.0	66.2	59.1	57.0
48	Marszal-Pomianowska et al. 2021	56.3	0.0	0.0	71.4	-	46.7
51	Arsene et al. 2022	-	-	-	-	-	68.0
52	Sborz et al. 2024	19.0	0.0	0.0	-	-	0.0
53	Meireles et al. 2022	32.4	0.0	0.0	-	-	-
57	Mazzoni et al. 2025	31.7	0.0	0.0	-	-	58.4
	Average	**35.3**	**37.5**	**8.8**	**69.5**	**71.6**	**54.0**
	Standard deviation	**9.4**	**51.8**	**9.8**	**4.1**	**11.0**	**23.6**

Note: DW = dishwasher; WM = washing machine; S = shower; B = bathtub; T = taps.

The HWR values reported in **Table 3** represent averages over the monitoring periods; however, this indicator is typically affected by seasonal variability. Among the reviewed studies, only Ahmed et al. (2015) provide a monthly characterization of HWR, showing a clear increase during colder months. During the cold season, higher HWR values may result not only from residents' preference or need to use larger volumes of hot water or water delivered at higher temperatures (Jacobs et al., 2018), but also from increased heat losses along the plumbing system. Under these conditions, water at the end uses may be mixed with a larger volume of hot water to achieve the desired temperature, thereby leading to higher HWC and, consequently higher HWR. However, the lack of outlet and end-use temperature measurements in many of the HWD datasets analyzed prevents a robust investigation of this aspect.

4.3. Third level: HWC parameter values

Metrics such as hot-water use frequency, average volume per use, and average duration per use are only sparsely investigated, both at the household scale (values reported in relation to 8 HWDs) and at the end-use scale (13 HWDs). As shown in **Table 4**, the available studies indicate an average of 14.63 hot-water uses/person/day at the household scale, ranging from a minimum of 7.30 (Kempton, 1988) to a maximum of 23.94 (Thomas et al., 2011) and with a standard deviation of 6.39 uses/person/day, while the corresponding volumes result in an average of 6.3 L/use (standard deviation 3.5 L/use), with values spanning from 2.0 L/use (Department for Energy Reduction and Net Zero, 2024) to 12.7 L/use (DEFRA, 2008).

At the end-use scale, the highest hot-water use frequency is observed for taps, averaging 9.57 uses/person/day, followed by showers (0.76 uses/person/day), washing machines (0.32 loads/person/day), dishwashers (0.16 loads/person/day), and bathtubs (0.07 uses/person/day). While acknowledging different underlying datasets and monitoring contexts, hot-water frequencies are comparable to the total-water frequencies reported by Mazzoni et al. (2023b) in the case of showers and bathtubs (0.74 and 0.11 uses/person/day), as well as washing machines and dishwashers (0.29 and 0.20 loads/person/day). In contrast, the average hot-water frequency for taps is markedly lower than the total-water frequency (16.98 uses/person/day), indicating that while shower and bathtub uses typically involve mixed water, a substantial share of tap uses rely on cold water only. Overall, these results suggest that hot-water use frequencies can reasonably approximate total-water frequencies for most end uses, whereas taps require explicit differentiation in hot-water demand modelling. Regarding volumes per use, bathtubs exhibit the largest average hot-water volumes (70.4 L/use), followed by showers (44.1 L/use), washing machines (37.7 L/load), and dishwashers (29.2 L/load), while taps show the smallest volumes (3.6 L/use). Comparison with total-consumption volumes reinforces the interpretation derived in the case of hot-water frequencies: hot-water volumes are lower than total-water volumes for bathtubs and showers (105.5 and 63.1 L/use, respectively) – confirming mixed or partial hot-water use – and for washing machines (92.2 L/load), reflecting predominantly cold-water operation with hot water limited to specific cycle phases (Mayer et al., 2000). Conversely, dishwashers and taps show hot-water volumes comparable to total-water values (17.6 L/load and 2.3 L/use), indicating that, if hot water is required, it is typically supplied throughout the entire use without mixing with cold water. Finally, duration of hot-water use emerges as the least documented parameter, reported in only 6 HWDs and mainly for showers and taps. Average durations of 6.1 min/use for showers and 33 s/use for taps align with the respective total-consumption durations (8.1 min/use and 25 s/use, respectively), suggesting that water use duration is independent of water temperature for these end uses.

Table 4. Summary of HWC parameter and values reported in the reviewed RHWSs.

HWD	**RHWS**	**Frequency of hot-water use (uses/person/day)**						**Volume per hot-water use (L/use)**						**Duration per hot-water use (min/use)**					
		Household	**DW**[a]	**WM**[a]	**S**	**B**	**T**	**Household**	**DW**[b]	**WM**[b]	**S**	**B**	**T**	**Household**	**DW**	**WM**	**S**	**B**	**T**[c]
4	Weihl and Kempton 1985 (*data from* Kempton 1988)	7.30	-	-	-	-	6.02	9.4	-	25.8	-	-	4.0	-	-	-	-	-	-
14	Lowenstein and Hiller 1998	-	0.16	0.26	0.67	0.08	-	-	40.0	29.3	37.6	57.5	-	-	-	-	-	-	-
17	Gleick et al. 2003	-	-	-	-	-	-	-	-	22.5	-	-	-	-	-	-	-	-	-
18	Jordan and Vajen 2001	-	-	-	1.00	0.07	14.00	-	-	-	40.0	140.0	1.0	-	-	-	5.0	10.0	60

19	Mayer et al. 2000 (*pre-retrofit*)	-	0.15	-	-	-	-	-	35.2	-	-	-	-	-	-	-	-	-	-
20	Henze et al. 2002	13.60	0.19	0.41	0.62	0.04	5.10	8.4	8.0	73.1	57.1	15.2	8.4	-	-	-	-	-	-
21	Mayer et al. 2003 (*pre-retrofit*)	-	0.13	-	-	-	-	-	33.7	-	-	-	-	-	-	-	-	-	-
23	CEC 2008	16.80	-	-	-	-	-	5.2	-	-	-	-	-	-	-	-	-	-	-
24	DEFRA 2008	9.60	-	-	-	-	-	12.7	-	-	-	-	-	-	-	-	-	-	-
26	Thomas et al. 2011	23.94	-	-	-	-	-	2.7	-	-	-	-	-	-	-	-	-	-	-
28	Schoenbauer et al. 2012	9.60	-	-	-	-	6.30	5.5	-	-	-	-	-	-	-	-	-	-	35
31	Henderson and Wade 2014	21.59	-	-	1.08	-	5.86	4.2	-	-	51.5	-	3.7	-	-	-	-	-	-
40	DeOreo et al. 2016	-	0.17	0.28	0.74	0.08	17.88	-	-	-	41.6	-	1.5	-	-	-	8.0	-	45
45	Marszal-Pomianowska et al. 2019	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5.0	-	20
48	Marszal-Pomianowska et al. 2021	-	-	-	0.42	-	11.84	-	-	-	-	-	-	-	-	-	6.7	-	11
56	Department for Energy Security and Net Zero 2024	-	-	-	-	-	-	2.0	-	-	37.0	69.0	3.0	-	-	-	5.8	11.0	29
	Average	**14.63**	**0.16**	**0.32**	**0.760**	**0.070**	**9.57**	**6.3**	**29.2**	**37.7**	**44.1**	**70.4**	**3.6**	**-**	**-**	**-**	**6.1**	**-**	**33**
	Standard deviation	**6.39**	**0.02**	**0.08**	**0.25**	**0.02**	**5.01**	**3.6**	**14.4**	**23.8**	**8.2**	**51.8**	**2.6**				**1.3**		**18**

Note: DW = dishwasher; WM = washing machine; S = shower; B = bathtub; T = taps; [a] loads/person/day; [b] L/load; [c] s/use

4.4. Fourth level: HWC daily profiles

HWC daily profiles are well documented at the household scale, with results reported for nearly half of the available HWDs (25 out of 59). The average profiles derived from each

HWD are depicted in **Figure 15a** and included in the **Supplementary Materials** (**Table S3**), while the corresponding box–whisker plots are shown in **Figure 15b**. Overall, the figure reveals that, similarly to total consumption, hot-water use exhibits markedly lower values during nighttime hours, when residents' activity is significantly reduced and nearly all fixtures requiring hot water cease operating, as widely acknowledged in the literature (Butler, 1991; Bagge and Johansson, 2011). Conversely, higher and more dispersed values occur during diurnal hours, with two distinct peaks reported across RHWSs (Ahmed et al., 2016; Becker and Stogsdill, 1990; DeOreo et al., 2016; Lee and Yim, 2021). The first and more pronounced peak appears in the morning, with an average hourly coefficient approaching 2, while a second, less marked peak occurs in the evening, with an average coefficient of about 1.5. In addition, HWC typically decreases around midday and during the late afternoon, as also observed by George et al. (2015). Overall, these peak periods reflect daily household routines and occupancy patterns (Vine et al., 1987; Marszal-Pomianowska et al., 2021), consistent with what is documented for total consumption (Mazzoni et al., 2023b): hot water is commonly used upon waking and before leaving home for work, school or other non-occupational activities, whereas evening peaks correspond to residents returning home and engaging in personal-hygiene and cleaning activities or meal preparation. The time intervals 6:00–8:00 and 19:00–20:00 show the greatest variability across HWDs, reflecting the diversity of domestic routines and hot-water use habits, also in relation to different geographic and socio-economic contexts.

The morning and evening peak periods observed in the literature are also reflected in daily HWC distributions derived from technical standards and guidelines (e.g., CEN, 2017; ASHRAE, 2019; UNI, 2019; Standards Australia/Standards New Zealand, 2021b). However, these sources generally allow only an approximate reconstruction of daily HWC profiles, as they are based on energy profiles with coarse temporal resolution, typically aggregated into multi-hour blocks rather than reported at hourly resolution. In addition, standards typically report more pronounced fluctuations, with peak coefficients of up to approximately 2.5. This contrast suggest a potential divergence between field-based consumption profiles and the more conservative assumptions adopted for infrastructure design. As a consequence, as reported in the literature, existing guidelines may lead to system oversizing and reduced efficiency (Averfalk et al., 2021).

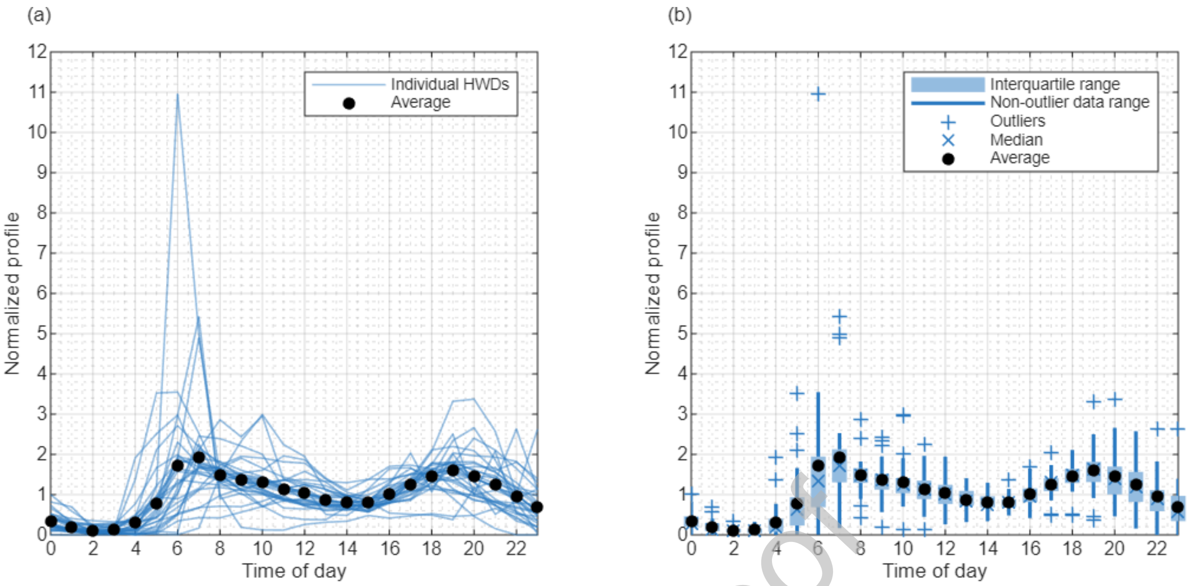


Figure 15. HWC (normalized) daily profiles: individual trends (a) and related box-whisker plots (b). An average profile is considered for each of the 25 HWDs in relation to which this information is available in the literature.

It is worth noting that, for some HWDs, the corresponding RHWSs report not only the average HWC profiles, but also information on profiles observed during specific periods or times of the year, e.g., weekdays (**Figure 16a**) *versus* weekends and holidays (**Figure 16b**), or cold season (**Figure 16d**) *versus* warm season (**Figure 16e**). Comparisons of the average HWC profiles observed at the household scale across different days of the week (13 HWDs) or seasons (9 HWDs) are presented in **Figure 16c** and **Figure 16f**, respectively. In addition, the values making up all the profiles reviewed in this study in relation to specific day types or seasons are included in the **Supplementary Materials**. (**Table S4–S7**).

Overall, the comparison of HWC profiles shown in **Figure 16** highlights two main aspects. First, a substantially different daily profile emerges on weekends compared to weekdays (**Figure 16c**), characterized by a reduction in the morning peak and a redistribution of HWC throughout the morning, while no significant changes are observed in the afternoon and evening. This pattern is likely explained by the reduction in work- and school-related activities on weekends, which delays morning water use and leads to a more evenly distributed HWC throughout the morning (Gelažanskas and Gamage, 2015; George et al., 2015; Marszal-Pomianowska et al., 2021), consistent with findings from household-scale water-use studies (Alvisi et al., 2021). Second, differences between cold and warm-season daily profiles are subtle. On average, a slight advance of morning HWC peak and a delay of the evening peak are observed during the warm season, likely driven by changes in daily routines and increased use during daylight hours. Specifically, some studies explicitly report that the evening hot-water peak tends to occur later in warm season compared to cold season. This trend has been clearly observed in RHWSs conducted in specific geographic contexts, particularly South Africa (Meyer and Tshimankinda, 1996; 1998b) and Brazil (Sborz et al., 2024), where the evening peak shifts forward by approximately one hour during the warm season. It should be noted that, in general, daily profiles of HWC are influenced not only by lifestyle (Perlman and Mills, 1985), cultural context (Ahmed et al., 2015), and geographic and climatic conditions, which explain differences between countries (De Santiago et al., 2017), but also, within the same context, by seasonal variations.

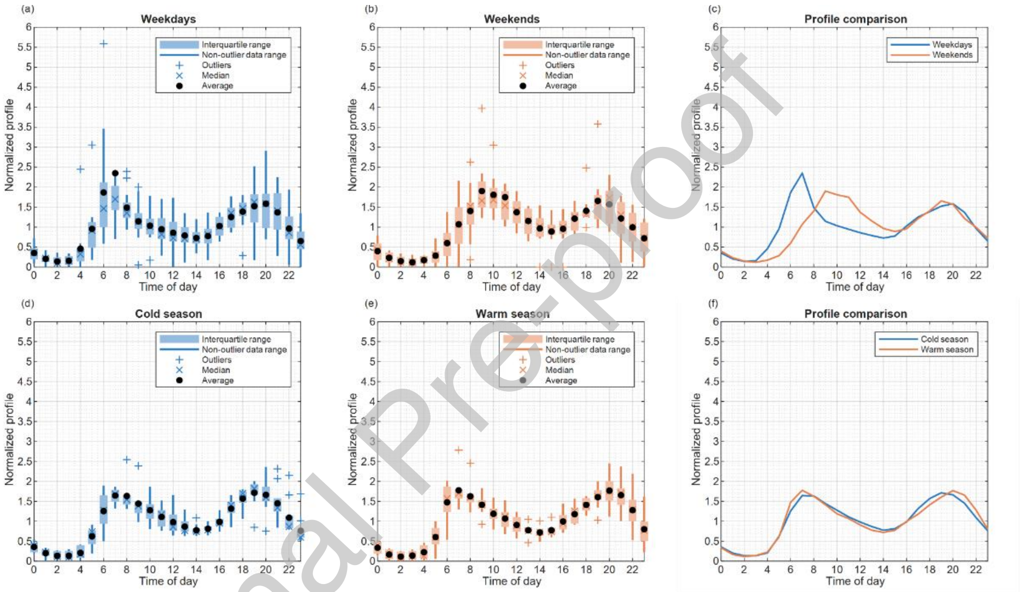


Figure 16. HWC (normalized) daily profiles: box-whisker plots of weekday (a) and weekend (b) profiles available in the literature (12 HWDs); comparison of weekday and weekend average profiles across the 12 reviewed HWDs (c); box-whisker plots of cold season (d) and warm season (e) profiles available in the literature (7 HWDs); comparison of winter and summer average profiles across the 7 reviewed HWDs (f).

At the end-use scale, information on daily HWC profiles are available for at least one end-use category in relation to 5 HWDs only. By way of example, Lowenstein and Hiller (1998) report the daily distribution of water uses of appliances, showers, and bathtubs across three sample households. Notably, one of these households provides the only documented instance of hot-water use (combined with cold water) for toilet flushing, implemented to prevent condensation on toilet fixtures. Here, different daily patterns emerge, depending on the end-use considered, and variations between weekdays and holidays are also observed. In addition to the above study, DEFRA (2008) presents daily profiles for all end-use categories, although limited to a single household, while Arsene et al. (2022) provide an example for a single tap. Mazzoni et al. (2025) report daily HWC profiles for two main end-use categories, namely showers and taps (the latter subdivided into kitchen and bathroom), across five households, highlighting shifts between hot- and cold-water peaks in kitchen sinks associated with different activities before and after dinner. However, hot water is separately monitored for only a single shower, limiting the characterization of this fixture across the sample. A HWD including shower profiles for a large group of households (ranging from about 150 to over 220 dwellings) is that by Sborz et al. (2022; 2024), although in this case showers are the only fixtures connected to hot water. Overall, the above outcomes confirm the scarcity of detailed end-use profiles of HWC across the reviewed RHWSs, with most data restricted to individual households or specific fixtures, thereby limiting the potential for broader generalizations across end uses and underscoring the information gap within the current literature.

4.5. Fifth level: HWC monthly profiles

Monthly HWC profiles are investigated, at the household scale, for 12 HWDs. Because most of these datasets originate from the Northern Hemisphere, the profiles from Southern Hemisphere countries – such as South Africa (Meyer and Tshimankinda, 1996; 1998a; 1998b), Brazil (Sborz et al., 2024), and Australia (Chao et al., 2015) – are aligned to the seasonal cycle of the former hemisphere, so as to ease the comparison of profiles and ensure consistency in their interpretation.

An overview of the normalized monthly profiles is presented in **Figure 17**, which displays both the individual profiles reported for each HWD (**Figure 17a**) and the corresponding box–whisker plots (**Figure 17b**), while all values making up each profile are included in the **Supplementary Materials** (**Table S8**). Overall, the trends indicate an increase in HWC during the winter months (i.e., October to March, referring to the Northern Hemisphere), when the monthly coefficient reveals values above the annual average. Specifically, peak consumption typically occurs in January, with an average coefficient exceeding 1.1. In contrast, HWC decreases during the summer, with a minimum of about 0.8 in July (referring to the Northern Hemisphere). With regard to the dispersion of values around the mean, **Figure 17b** shows that the widest interquartile ranges occur around the peak winter period (December–February; referring to the Northern Hemisphere), highlighting that the reviewed RHWSs exhibit the greatest variability when HWC is typically the highest. It is worth noting that three of the profiles reported in **Figure 17a** exhibit a similar pattern that slightly deviates from the general trend. These trends are derived from the studies by Meyer and Tshimankinda (1996, 1998a and 1998b), all of which were conducted in South Africa. The observed uniformity is therefore likely due to the consistent methodology applied and the specific socio-climatic characteristics of the study location.

Although the seasonal trend of total-water consumption is known to typically peak during the warm season and decrease in winter (Rathnayaka et al., 2015; Potter et al., 2022), the RHWS by Chao et al. (2015) appears to be the only study that clearly demonstrates an inverse relationship between the monthly profiles of HWC and total-water consumption, highlighting that peak summer consumption is fully attributable to increased cold-water use. In addition, while not explicitly comparing HWC and total-water consumption profiles, Abrams and Shedd (1996) and Gerin et al. (2014) show that monthly HWC profiles are inversely related to air temperature profiles. Similarly, Sborz et al. (2024) show that HWC reaches its lowest values when air temperature is at its maximum, even though the monitored households exhibit limited seasonal variation in total-water consumption.

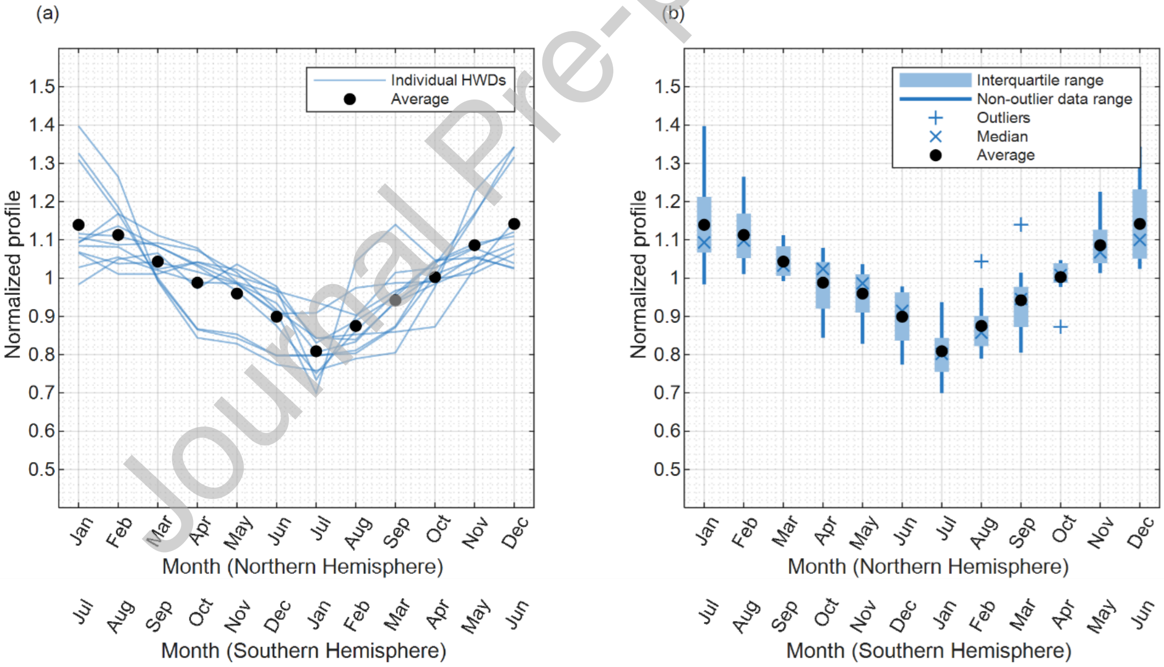


Figure 17. HWC (normalized) monthly profiles: individual profiles (a) and related box-whisker plots (b). An average trend is considered for each of the 12 HWDs in relation to which this information is available in the literature.

Finally, although they do not fully meet the criteria required for this level of the analysis, several RHWSs nonetheless provide partial indications of seasonal HWC trends of the related HWDs, either through limited temporal coverage or by reporting summary statistics rather than continuous (i.e., year-long) profiles. For instance, Gilbert et al. (1985) report average consumptions of 265 and 216 L/household/day for January and July, respectively, illustrating a basic cold–hot season contrast without presenting a full seasonal trend. Similarly, Merrigan et al. (1988) observe 241 and 184 L/household/day for January and July, highlighting comparable seasonal differences, while Papakostas et al. (1995) provide the average per capita HWC for all seasons, in relation to each monitored multi-apartment building. Ahmed et al. (2016) align with this approach by reporting 47, 39, and 43 L/person/day for January, August, and November, respectively, again suggesting monthly variation but without providing a continuous profile, whereas Lee and Yim (2021) report 269 and 129 L/household/day for winter and summer, respectively, though without specifying particular months. Lastly, the Department for Energy Security and Net Zero (2024) reveals seasonal deviations of 5 L/household/day with respect to yearly average.

Regarding the assessment of HWC monthly profiles at the end-use scale, it is worth noting that none of the reviewed RHWSs provide monthly profiles of hot-water use for individual end-use categories. The only exception is the HWD examined by Sborz et al. (2024), which reports monthly HWC for showers which are the sole fixtures connected to the hot-water system; therefore, the household-scale monthly profile effectively corresponds to the monthly profile of shower HWC. Despite this isolated case, the absence of end-use-specific monthly trends across the reviewed studies indicates that seasonal profiling of HWC at fixture scale has not yet been addressed in the scientific literature and suggests promising opportunities for future research. The scarcity of such information is partly attributable to the fact that end-use monitoring – both for hot water (as discussed the *Study characteristics* section) and for total water consumption (Mazzoni et al., 2023b) – typically relies on fine temporal resolutions. These sampling resolutions generally make year-long monitoring impractical due to the large volume of data generated and the associated technical and logistical constraints, such as increased storage requirements and limitations in product availability (Cominola et al., 2018).

5. Summary of Study Findings and Limitations

This section summarizes the main findings of the study together with the main limitations and critical gaps identified in the reviewed literature on field-based HWC data, primarily related to data availability, completeness, and comparability.

Overall, the multi-level analysis revealed the following main findings:

- Daily per capita HWC shows an average of about 60 L/person/day at the household scale, with substantial variability across contexts and a gradual decline from 1985 to 2025, reflecting technological improvements, behavioral changes, and regulatory measures, and with showers consistently accounting for the largest share of end-use HWC.
- Roughly one-third of household water consumption is hot, with personal-hygiene-related fixtures showing the highest shares (typically accounting for about half to two-thirds of total use), whereas appliances are more variable due to differences in connection standards.
- Taps are the most frequent hot-water uses (with nearly 10 uses/person/day), followed by showers, while bathtubs and appliances occur less frequently. However, showers and bathtubs account for the largest volumes of hot water per use (45–70 L/use), whereas taps show the smallest (3–4 L/use).
- Daily household HWC follows a clear pattern, with low night-time use and two distinct morning and evening peaks that shift on weekends and, to a lesser extent, across seasons.
- Monthly profiles reveal higher household HWC in winter and lower use in summer, while monthly end-use profiles remain largely undocumented and limited to very few cases (e.g., showers).

The main limitations and gaps identified in the reviewed literature are summarized below:

- Most studies focus on household-scale daily per capita HWC and consumption profiles, while fewer report hot-water ratios, hot-water use specific parameters, or monthly HWC profiles. End-use data are particularly scarce, reflecting the limited number of detailed field measurements at the fixture scale. In particular, specific appliance-scale contributions to HWC (i.e., due to dishwashers and washing machines) are rarely investigated, especially when internal electric heating elements are used, which may lead to underestimation of HWC.
- The characterization of hot-water systems is often incomplete, as HWC data are hardly ever coupled with thermal measurements at inlet, outlet, and end-use points. This limits the ability to discriminate between the share of HWC due to user demand and that driven by system-related heat losses, highlighting the need for comprehensive, standardized datasets integrating water and temperature

measurements. In addition, inconsistencies in system configurations, such as the presence of storage hot-water tanks (potentially affecting the HWC profile), further reduce data comparability.

- Seasonal HWC profiles are often based on broad distinctions between cold and warm periods, with limited transparency regarding the specific months considered. Moreover, information on how *Daylight Saving Time* transitions are handled is generally absent, despite its potential relevance for the interpretation and comparison of daily HWC profiles.
- A geographic bias is evident, with most studies concentrated in North America and Northern Europe. This spatial imbalance limits global comparability and suggests that current benchmarks may be primarily representative of specific regions.
- Freely accessible and standardized HWC datasets remain scarce, requiring reliance on values reported in the literature and often lacking sufficient metadata for deeper analyses. Although additional datasets have recently been made available in open-access repositories (e.g., Walnum et al., 2021; Schattmann et al., 2025; Graupera Serra et al, 2026), they frequently lack detailed documentation on monitoring protocols, units, system configurations, or methodological frameworks. This limited metadata availability restricts their integration into the present analysis.

In light of the above limitations, future research should prioritize expanding field measurements at the end-use scale and improving coverage in under-represented geographic regions. Efforts should also focus on the development of standardized, open-access databases with comprehensive metadata, including detailed methodological descriptions and temperature data at key system locations (inlets, outlets, and end-use points), which are essential for improved energy-management and water-heating strategies.

6. Conclusions

This study provides a systematic and standardized review of residential hot-water consumption (HWC) based on field data from 59 hot-water databases across diverse contexts, revealing average values, usage parameters, and temporal distributions, as well as their similarities and differences across contexts. The key outcome is the establishment of a reference framework for HWC characterization, based on the systematic comparison of consumption values, profiles, and end-use behaviors. By integrating data across annual, seasonal, and hourly scales, the study provides a robust basis for advancing knowledge on residential HWC and supporting comparative analyses and modeling. This, in turn, has direct implications for building-scale energy-performance assessments, where accurate estimation of HWC is essential for evaluating the water–

energy nexus. In addition, the results can support the refinement of technical standards and guidelines for plumbing system sizing and water-heating systems, while contributing to the development of water- and energy-efficient technologies and strategies.

Author contributions

Conceptualization: F.M., V.M., M.B., S.A.; Data curation: F. M., V.M.; Formal analysis: F.M., V.M.; Investigation: F.M., V.M.; Methodology: F.M., V.M., M.B., S.A.; Software: F. M., V.M.; Resources: F.M., V.M., M.B., S.A.; Visualization: F.M., V.M., M.B., S.A.; Validation: F.M., V.M., M.B., S.A.; Writing—original draft: F. M., V.M.; Writing—review & editing: F.M., V.M., M.B., S.A.; Supervision: S. A., M. B.; Project administration: S.A. All authors have read and agreed to the published version of the manuscript.

Data availability

All data obtained from the analyses are included within the study or in the Supplementary Materials, alongside the MATLAB R2025b® code developed to perform the analyses and generate the figures presented.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary Materials

Supplementary material associated with this article (**Table S1-S8** and MATLAB R2019a® code) can be found in the online version.

References

1. Abdallah, A. M., & Rosenberg, D. E. (2014). Heterogeneous residential water and energy linkages and implications for conservation and management. *Journal of Water Resources Planning and Management*, 140(3), 288–297. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000340
2. Abrams, D. W., & Shedd, A. C. (1996). Effect of Seasonal Changes in Use Patterns and Cold Inlet Water Temperature on Water-Heating Loads. *ASHRAE Transactions*, *102*(pt. 1), 1038–1053, AT-96-18-3.
3. Agudelo-Vera, C., Avvedimento, S., Boxall, J., Creaco, E., de Kater, H., Di Nardo, A., Djukic, A., Douterelo, I., Fish, K. E., Iglesias Rey, P. L., Jacimovic, N., Jacobs, H. E., Kapelan, Z., Martinez Solano, J., Montoya Pachongo, C., Piller, O., Quintiliani, C., Rucka, J., Tuhovcak, L., & Blokker, M. (2020). Drinking water temperature around the globe: Understanding, policies, challenges and opportunities. *Water*, 12(4), 1049. https://doi.org/10.3390/w12041049.
4. Aguirre, F., Magnago, F., & Alemany, J. (2019). Constructing hot water load profile: An agent-based modeling approach. *IEEE Transactions on Sustainable Energy*, 10(2), 790–799. https://doi.org/10.1109/TSTE.2018.2847673
5. Ahmed, K., Pylsy, P., & Kurnitski, J. (2015). Monthly domestic hot water profiles for energy calculation in Finnish apartment buildings. *Energy and Buildings*, *97*, 77–85. https://doi.org/10.1016/j.enbuild.2015.03.051.
6. Ahmed, K., Pylsy, P., & Kurnitski, J. (2016). Hourly consumption profiles of domestic hot water for different occupant groups in dwellings. *Solar Energy*, *137*, 516–530. https://doi.org/10.1016/j.solener.2016.08.033.
7. Alvisi, S., Franchini, M., Luciani, C., Marzola, I., & Mazzoni, F. (2021). Effects of the COVID-19 Lockdown on Water Consumptions: Northern Italy Case Study. *Journal of Water Resources Planning and Management*, *147*(11), 05021021. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001481.
8. Anderson, D. L., Mulville-Friel, D., & Nero, W. L. (1993). The impact of water conserving fixtures on residential water use characteristics in Tampa, Florida. *Proceedings of Conserve93-The New Water Agenda*. Las Vegas, Nevada (US).
9. Aquacraft. (2005). *Water and Energy Savings from High-Efficiency Fixtures and Appliances in Single-Family Homes* (Report: US Environmental Protection Agency).
10. Arsene, D., Predescu, A., Pahontu, B., Chiru, C. G., Apostol, E.-S., & Truică, C.-O. (2022). Advanced Strategies for Monitoring Water Consumption Patterns in Households Based on IoT and Machine Learning. *Water*, *14*, 2187. https://doi.org/10.3390/w14142187.
11. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). (2019). ASHRAE handbook: HVAC applications (Chapter: Service water heating). ASHRAE.
12. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) (2020). *Guideline 12. Managing the Risk of Legionellosis Associated with Building Water Systems*. ASHRAE.
13. Averfalk, H., Möllerström, E., & Ottermo, F. (2021). Domestic hot water design and flow measurements. *Energy Reports*, 7, 304–310. https://doi.org/10.1016/j.egyr.2021.08.142.

14. Bagge, H., & Johansson, D. (2011). Measurements of household electricity and domestic hot water use in dwellings and the effect of different monitoring time resolution. *Energy*, *36*, 2943–2951. https://doi.org/10.1016/j.energy.2011.02.037.
15. Bayle, R., Reyboz, M., Lomet, A., Cook, V., & Mermillod, M. (2024). Continuously Learning Prediction Models for Smart Domestic Hot Water Management. *Energies*, *17*(18), 4734. https://doi.org/10.3390/en17184734.
16. Beausoleil-Morrison I. (2008). *An experimental and simulation-based investigation of the performance of small-scale fuel cell and combustion-based cogeneration devices serving residential buildings* (Report: IEA Annex 42).
17. Becker, B. R., & Stogsdill, K. E. (1990). Development of a Hot Water Use Data Base. *ASHRAE Transactions*, *96*(pt. 2), 422–427, 3431.
18. Berkeley L., & Lutz J. (2008). *Water Heaters And Hot Water Distribution Systems* (Report: CEC-500-2005-007). California Energy Commission.
19. Binks, A. N., Kenway, S. J., Lant, P. A., & Head, B. W. (2016). Understanding Australian household water-related energy use and identifying physical and human characteristics of major end uses. *Journal of Cleaner Production*, *135*, 892–906. https://doi.org/10.1016/j.jclepro.2016.06.091.
20. Binks, A. N., Kenway, S. J., & Lant, P. A. (2017). The effect of water demand management in showers on household energy use. *Journal of Cleaner Production*, *157*, 177–189. https://doi.org/10.1016/j.jclepro.2017.04.128.
21. Bøhm, B. (2013). Production and distribution of domestic hot water in selected Danish apartment buildings and institutions. Analysis of consumption, energy efficiency and the significance for energy design requirements of buildings. *Energy Conversion and Management*, *67*, 152–159. https://doi.org/10.1016/j.enconman.2012.11.002.
22. Bors, J., O'Brien, K. R., Kenway, S. J., & Lant, P. A. (2017). Regional scale variability of cold water temperature: Implications for household water related energy demand. *Resources, Conservation and Recycling*, 124, 107–115. https://doi.org/10.1016/j.resconrec.2017.05.001
23. Bouchelle, M. P., Parker, D. S., & Anello, M. T. (2000). Factors Influencing Water Heating Energy Use And Peak Demand In A Large Scale Residential Monitoring Study. *Symposium on Improving Building Systems in Hot and Humid Climates*. San Antonio, Texas (US).
24. Blokker, E. J. M., van Osch, A. M., Hogeveen, R., & Mudde, C. (2013). Thermal energy from drinking water and cost benefit analysis for an entire city. *Journal of Water and Climate Change*, 4(1), 11–16. https://doi.org/10.2166/wcc.2013.010.
25. Blokker, E. J. M., Vreeburg, J. H. G., & van Dijk, J. C. (2010). Simulating residential water demand with a stochastic end-use model: SIMDEUM. *Journal of Water Resources Planning and Management*, *136*, 19–26. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000002.
26. Butler, D. (1991). A Small-Scale Study of Wastewater Discharges from Domestic Appliances. *Water and Environment Journal*, *5*, 178–184. https://doi.org/10.1111/j.1747-6593.1991.tb00605.x.
27. Canale, L., Cholewa, T., Ficco, G., Siuta-Olcha, A., Di Pietra, B., Kołodziej, P., & Dell'Isola, M. (2023). The role of individual metering in reducing domestic hot water

consumption in residential buildings: A long-term evaluation. *Journal of Building Engineering*, *73*, 106734. https://doi.org/10.1016/j.jobe.2023.106734.

28. CDC (Centers for Disease Control and Prevention) (2017). *Developing a water management program to reduce Legionella growth and spread in buildings*. U.S. Department of Health and Human Services, Atlanta, GA, United States.
29. CEN (European Committee for Standardization) (2005). *EN 806-2. Specifications for installations inside buildings conveying water for human consumption – Part 2: Design*. CEN.
30. CEN (European Committee for Standardization). (2017). *EN 12831: Heating systems in buildings – Method for calculation of the design heat load*. CEN.
31. Chao, P. R., Umapathi, S., & Saman, W. (2015). Water consumption characteristics at a sustainable residential development with rainwater-sourced hot water supply. *Journal of Cleaner Production*, *109*, 190–202. https://doi.org/10.1016/j.jclepro.2015.04.091.
32. Chen, Y., Fuchs, H., Schein, J., Franco, V. H., Stratton, H., Burke, T. A., & Dunham, C. (2021). Water heating energy use reductions from EPA WaterSense lavatory plumbing fittings. *Resources, Conservation and Recycling*, 174, 105781. https://doi.org/10.1016/j.resconrec.2021.105781
33. Chen, Y., Fuchs, H., Schein, J., Franco, V., Stratton, H., & Dunham, C. (2020). *Calculating Average Hot Water Mixes of Residential Plumbing Fittings: Using the ANSI 301-2019 Hot Water Draw Model and National Residential Data to Estimate Hot Water Use in Showerheads and Lavatory Faucets* (Report: US Environmental Protection Agency).
34. Chmielewska, A., Szulgowska-Zgrzywa, M., & Danielewicz, J. (2017). Domestic hot water consumption in multi-apartment buildings. *Proceeding of EKO-DOK 2017*, Boguszów-Gorce (PL), 00014.
35. Chmielewska, A. (2025). Characteristics of Domestic Hot Water Consumption Profiles in Multi-Family Buildings for Energy Modeling Purposes. *Energies*, *18*, 4578. https://doi.org/10.3390/en18174578.
36. Clarivate. (2025). *Web of Science Core Collection*. Retrieved November 11, 2025, from https://www.webofscience.com.
37. Cominola A., Giuliani M., Castelletti A., Rosenberg D. E., & Abdallah A. M. (2018). Implications of Data Sampling Resolution on Water Use Simulation, End-Use Disaggregation, And Demand Management. *Environmental Modelling & Software*, *102*, 199–212. https://doi.org/10.1016/j.envsoft.2017.11.022.
38. Cominola, A., Nguyen, K. A., Giuliani, M., Stewart, R. A., Maier, H. R., & Castelletti, A. (2019). Data Mining to Uncover Heterogeneous Water Use Behaviors from Smart Meter Data. *Water Resources Research*, *55*, 9315–9333. https://doi.org/10.1029/2019WR024897.
39. Cominola, A., Preiss, L., Thyer, M., Maier, H. R., Prevos, P., Stewart, R. A., & Castelletti, A. (2023). The determinants of household water consumption: A review and assessment framework for research and practice. *NPJ Clean Water*, *6*, 12. https://doi.org/10.1038/s41545-022-00208-8.
40. De Santiago J., Rodriguez-Villalón O., & Sicre B. (2017). The generation of domestic hot water load profiles in Swiss residential buildings through statistical predictions. *Energy and Buildings*, *141*, 341–348. https://doi.org/10.1016/j.enbuild.2017.02.045.

41. Department for Energy Security and Net Zero. (2024). *Domestic hot water use in the UK. Observations on hot-water use from connected devices*. United Kingdom. Retrieved April 1, 2026, from https://www.gov.uk/government/publications/domestic-hot-water-use-in-the-uk
42. Department for Environment, Food and Rural Affairs (DEFRA). (2008). *Measurement of Domestic Hot Water Consumption in Dwellings* (Report: U.K. Government, Energy Saving Trust).
43. DeOreo, W. B., Mayer, P. W., Dziegielewski, B., & Kiefer, J. (2016). *Residential End Uses of Water, Version 2*. Water Research Foundation. Denver, Colorado (USA).
44. DeOreo W. B., & Mayer P. (2000). *The End Uses of Hot Water in Single Family Homes from Flow Trace Analysis*. Aquacraft Inc. Boulder, Colorado (USA).
45. Di Mauro A., Cominola C., Castelletti A., & Di Nardo A. (2021). Urban Water Consumption at Multiple Spatial and Temporal Scales. A Review of Existing Datasets. *Water*, *13*(1), 36. https://doi.org/10.3390/w13010036.
46. DIN (German Institute for Standardization). (2011). *DIN 4708: Central hot water supply systems – Calculation of heat demand and system sizing*. DIN.
47. DIN (German Institute for Standardization). (2012). *DIN 1988 200: Technical rules for drinking water installations – Part 200: Installation type A (closed systems) (Standard No. DIN 1988 200:2012)*. DIN.
48. Dutch Ministry of Infrastructure and Water Management (2004, updated). *Drinking Water Decree (Drinkwaterbesluit) and Legionella Prevention Regulations*. Government of the Netherlands.
49. DVGW (German Technical and Scientific Association for Gas and Water) (2004). *W 551. Drinking water heating and distribution systems – Technical measures to reduce Legionella growth*. DVGW
50. European Centre for Disease Prevention and Control. (2017). *Legionnaires' disease prevention and control*. European Centre for Disease Prevention and Control.
51. Edwards K., & Martin L. (1995). A Methodology for Surveying Domestic Water Consumption. *Water and Environment Journal*, *9*(5), 477–488. https://doi.org/10.1111/j.1747-6593.1995.tb01486.x.
52. Edwards, S., Beausoleil-Morrison I., & Laperrière A. (2015). Representative hot water draw profiles at high temporal resolution for simulating the performance of solar thermal systems. *Solar Energy*, *111*, 43–52. https://doi.org/10.1016/j.solener.2014.10.026.
53. Elsevier. (2025). *Scopus: The abstract and citation database of peer-reviewed literature*. Retrieved November 11, 2025, from https://www.scopus.com.
54. Fairey P., & Parker D. (2004). *A Review of Hot Water Draw Profiles Used in Performance Analysis of Residential Domestic Hot Water Systems* (Report: FSEC-RR-56-04).
55. FIOH (Finnish Institute of Occupational Health. (2018*). Legionella bacteria in water systems – prevention and control*. Finland: FIOH.
56. French Ministry of Health. (2005). *Circular on the prevention of legionellosis risk in domestic hot water systems*. France: Ministry of Health.
57. Fuentes E., Arce L., & Salom J. (2018). A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis.

Renewable and Sustainable Energy Reviews, *81*, 1530–1547. https://doi.org/10.1016/j.rser.2017.05.229.

58. Gavaldà, L., Garcia Nuñez, M., Quero, S., & Gutierrez Milla, C. (2019). Role of hot water temperature and water system use on Legionella control in a tertiary hospital: An 8-year longitudinal study. *Water Research*, 149, 460–466. https://doi.org/10.1016/j.watres.2018.11.032.
59. Gelažanskas L., & Gamage A. A. (2015). Forecasting Hot Water Consumption in Residential Houses. *Energies*, *8*, 12702–12717. https://doi.org/10.3390/en81112336.
60. George D., Pearre N. S., & Swan L. G. (2015). High resolution measured domestic hot water consumption of Canadian homes. *Energy & Buildings*, *109*, 304–315. https://doi.org/10.1016/j.enbuild.2015.09.067.
61. Gerin O., Bleys B., & De Cuyper K. (2014). Seasonal variation of hot and cold water consumption in apartment buildings. *Proceeding of the CIBW062 Symposium 2014*, São Paulo (BR).
62. Gilbert Associates Inc. (1985). EPRI EA-006, Research Project 1101-1. Palo Alto, CA: Electric Power Research Institute.
63. Gleick P. H., Haasz D., Henges-Jeck C., Srinivasan V., Wolff G., Cushing K. K., & Mann A. (2003). *Waste Not, Want Not: The Potential for Urabn Water Conservation in California.* Pacific Institute. ISBN: 1-893790-09-6.
64. Google. (2025). *Google Scholar*. Retrieved November 11, 2025, from https://scholar.google.com.
65. Graf, C., Pärisch, P., Marszal-Pomianowska, A., Frandsen, M., Bendinger, B., & Cadenbach, A. (2024). Domestic hot water systems in well-insulated residential buildings: A comparative simulation study on efficiency and hygiene. *Energy*, *313*, 133587. https://doi.org/10.1016/j.energy.2024.133587.
66. Graupera Serra, O., B. Rosado, A., Puga Creus, E., Fernandez, I., Burillo, C., Escuder Folch, S., Calvo, A., Lebron Casas, L., Villa González, C., Rosado, D., Baena Miret, S., Trejo Ramírez, K. A., & Huerta, I. (2026). *hihAigua dataset* [Data set]. Zenodo. https://doi.org/10.5281/zenodo.18456405
67. Hall, R., O'Brien, K. R., Kenway, S., & Memon, F. A. (2024). Heat loss from non-circulating domestic hot water pipes increases water consumption and energy demand. *Resources, Conservation and Recycling*, *206*, 107658. https://doi.org/10.1016/j.resconrec.2024.107658.
68. Hellenic Ministry of Health. (2017). *National guidelines for the prevention and control of Legionella in water systems*. Greece: Ministry of Health.
69. Henderson H., & Wade J. (2014). *Disaggregating Hot Water Use and Predicting Hot Water Waste in Five Test Homes*. US Department of Energy, Energy Efficiency & Renewable Energy.
70. Henze, G. P., Tiller, D. K., Fischer, M. A., & Rieger, M. (2002). Comparison of event inference and flow trace signature methods for hot-water end-use analysis. *ASHRAE Transactions*, *108*(pt. 2), 467–479, HI-02-8-1.
71. Hirst, E., Goeltz, R., & Hubbard, M. (1987). Determinants of electricity use for residential water heating: The Hood River Conservation Project. *Energy Conservation Management*, *27*(2), 171–178. https://doi.org/10.1016/0196-8904(87)90072-0.

72. Health and Safety Executive (2013). *Legionnaires' disease: The control of Legionella bacteria in water systems (L8 Approved Code of Practice).* United Kingdom: Health and Safety Executive.
73. Jacobs, H. E., Botha, B. E., & Blokker, E. J. M. (2018). Household hot water temperature: An analysis at end-use level. *Proceedings of the 1st International WDSA/CCWI 2018 Joint Conference*. Kingston, Ontario, Canada.
74. Jordan U., & Vajen K. (2001). *Realistic Domestic Hot-Water Profiles in Different Time Scales*. Solar Heating and Cooling Program of the International Energy Agency.
75. Khalkhali M., Dilkina B., & Mo W. (2021). The role of climate change and decentralization in urban water services: A dynamic energy-water nexus analysis. *Water Research*, *207*, 117830. https://doi.org/10.1016/j.watres.2021.117830.
76. Kempton W. (1988). Residential hot water: A behaviorally-driven system. *Energy*, *13*(1), 107–114. https://doi.org/10.1016/0360-5442(88)90083-7.
77. Kitzberger, T., Kilian, D., Kotik, J., & Pröll, T. (2019). Comprehensive analysis of the performance and intrinsic energy losses of centralized Domestic Hot Water (DHW) systems in commercial (educational) buildings. *Energy & Buildings*, *195*, 126–138. https://doi.org/10.1016/j.enbuild.2019.05.016.
78. Knight I., Kreutzer N., Manning M., Swinton M., & Ribberink H. (2007). *European and Candian non-HVAI Electric and DHW Load Profiles for Use in Simulating the Performance of Residential Cogeneration Systems* (Report: IEA/ECBCS, Annex 42).
79. Koop S. H. A., Clevers S. H. P., Blokker E. J. M., & Brouwer S. (2021). Public Attitudes towards Digital Water Meters for Households. *Sustainability*, *13*(11), 6440. https://doi.org/10.3390/su13116440.
80. Lee, Jae Yong, & Yim, Taesu (2021). Energy and flow demand analysis of domestic hot water in an apartment complex using a smart meter. *Energy*, *229*, 120678. https://doi.org/10.1016/j.energy.2021.120678.
81. Lowenstein, A., & Hiller, C. C. (1998). Disaggregating residential hot-water use (Part II). *ASHRAE Transactions*, *104*(pt. 1), 1852–1863, SF-98-31-2.
82. Luciani, C., Casellato, F., Alvisi, S., & Franchini, M. (2019). Green Smart Technology for Water (GST4Water): Water loss identification at user level by using smart metering systems. *Water*, *11*, 405. https://doi.org/10.3390/w11030405.
83. Makonin, S. Ellert B., Bajić I. V., & Popowich F. (2016). Electricity, water, and natural gas consumption of a residential house in Canada from 2012 to 2014. *Scientific Data*, *3*, 160037. https://doi.org/10.1038/sdata.2016.37.
84. Marszal-Pomianowska, A., Valev, B., Georgieva, V., Larsen, O. K., Jensen, R. L., & Zhang, C. (2019). High resolution measuring system for domestic hot water consumption. Development and field test. *Energy Procedia*, *158*, 2859–2864. https://doi.org/10.1016/j.egypro.2019.01.1022.
85. Marszal-Pomianowska, A., Jensen, R. L., Pomianowski, M., Larsen, O. K., Jørgensen, J. S., & Knudsen, S. S. (2021). Comfort of Domestic Water in Residential Buildings: Flow, Temperature and Energy in Draw-Off Points: Field Study in Two Danish Detached Houses. *Energies*, *14*, 3314. https://doi.org/10.3390/en14113314.
86. Masiello J. A., & Parker D. S. (1992). Factors Influencing Water Heating Energy Use and Peak Demand in a Large Scale Residential Monitoring Study. In *Residential*

Buildings: Technologies, Design, Performance Analysis, and Building Industry Trends (pp. 1157–1170).

87. Mayer, P. W., DeOreo, W. B., & Lewis, D. M. (2000). *Seattle Home Water Conservation Study: the Impacts of High Efficiency Plumbing Fixture Retrofits in Single-Family Homes*. Aquacraft, Inc. Water Engineering and Management, Boulder, Colorado (US).
88. Mayer, P. W., DeOreo, W. B., Towler, E., & Lewis, D. M. (2003). *Residential Indoor Water Conservation Study: Evaluation of High Efficiency Indoor Plumbing Fixture Retrofits in Single-Family Homes in the East Bay Municipal Utility District Service Area*. Aquacraft, Inc. Water Engineering and Management, Boulder, Colorado (US).
89. Mazzoni F., Alvisi S., Franchini M., & Blokker M. (2023a). Exploiting high-resolution data to investigate the characteristics of water consumption at the end-use level: A Dutch case study. *Water Research and Industry*, *29*, 100198. https://doi.org/10.1016/j.wri.2022.100198.
90. Mazzoni F., Alvisi S., Blokker M., Buchberger S. G., & Castelletti A. et al. (2023b). Investigating the characteristics of residential end uses of water: A worldwide review. *Water Research*, *230*(15), 119500. https://doi.org/10.1016/j.watres.2022.119500.
91. Mazzoni, F., Marsili, V., & Alvisi, S. (2025). Characterizing Hot-Water Consumption at Household and End-Use Levels Based on Smart-Meter Data. *Water*, *17*, 1906. https://doi.org/10.3390/w17131906.
92. Meireles, I., Sousa, V., Bleys, B., & Poncelet, B. (2022). Domestic hot water consumption pattern: Relation with total water consumption and air temperature. *Renewable and Sustainable Energy Reviews*, *157*, 112035. https://doi.org/10.1016/j.rser.2021.112035.
93. Merrigan, T. J. (1988). Residential hot-water use in Florida and North Carolina. *ASHRAE Transactions*, *94*(pt. 1), 1099–1109, DA-88-10-2.
94. Meyer, J. P., & Tshimankinda, M. (1996). Domestic hot water consumption by developing communities in South African traditional houses. *Energy*, *21*(12), 1101–1106. https://doi.org/10.1016/0360-5442(96)00063-1.
95. Meyer J. P., & Tshimankinda M. (1998a). Domestic Hot-Water Consumption In South African Apartments. *Energy*, *23*(1), 61–66. https://doi.org/10.1016/S0360-5442(97)00069-8.
96. Meyer J. P., & Tshimankinda M. (1998b). Domestic Hot Water Consumption In South African Townhouses. *Energy Conversion and Management*, *39*(7), 679–684. https://doi.org/10.1016/S0196-8904(97)00048-4.
97. Milligan, N. H. (1987). *Performance of Domestic Hot Water Systems in Five Apartment Buildings (Part II-Analysis and results)* (Report: OHRD 87-53-K).
98. NIPH (Norwegian Institute of Public Health). (2016). *Prevention of Legionella in building water systems*. Oslo, Norway: NIPH.
99. NRCan (Natural Resources Canada). (n.d., accessed 2025). *HOT2000: Residential Energy Simulation Tool*. Government of Canada.
100. Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *The BMJ*, *372*: n160. https://doi.org/10.1136/bmj.n160.

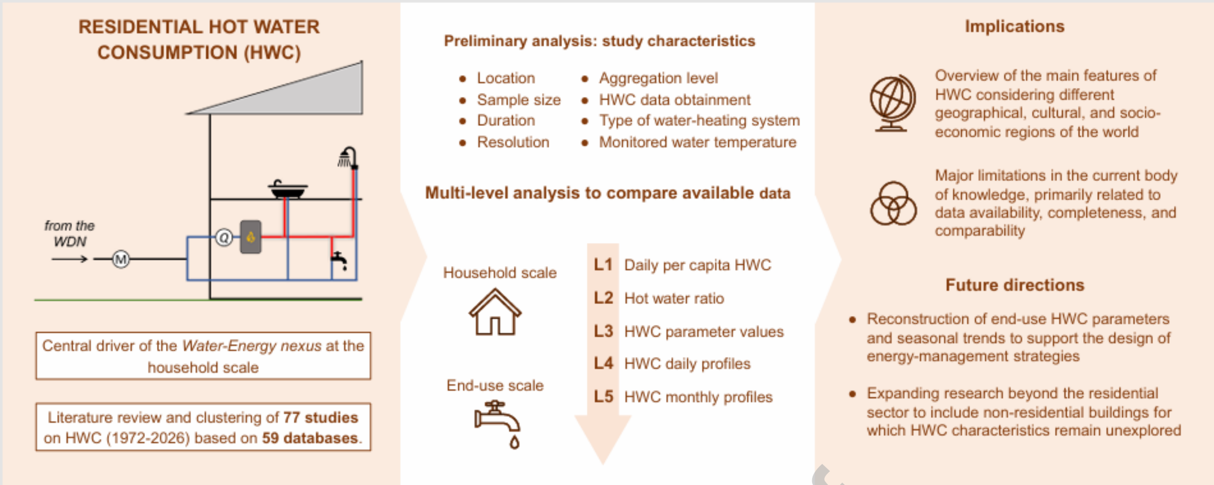
101. Papakostas, K. T., Papageorgiou, N. E., & Sotiropoulos, B. A. (1995). Residential hot water use patterns in Greece. *Solar Energy*, *54*(6), 369–374. https://doi.org/10.1016/0038-092X(95)00014-I.
102. Parker, D. S., Fairey, P. W., & Lutz, J. D. (2015). Estimating Daily Domestic Hot-Water Use in North American Homes. *ASHRAE Transactions*, *121*(pt. 2), AT-15-021.
103. Perlman, M., & Mills, B. E. (1985). Development of residential hot-water use patterns. *ASHRAE Transactions, Research Report, RP-430*.
104. Pesantez, J. E., Berglund, E. Z., & Kaza, N. (2020). Smart meters data for modeling and forecasting water demand at the user-level. *Environmental Modelling & Software*, 125, 104633. https://doi.org/10.1016/j.envsoft.2020.104633.
105. Potter, L. B., Tremaine, D. M., & Banner, J. L. (2022). Predictors of Variations in Residential Water Consumption in Central Texas. *Water*, 14(11), 1804. https://doi.org/10.3390/w14111804.
106. Rankin, R., & Rousseau, P. G. (2006). Sanitary hot water consumption patterns in commercial and industrial sectors in South Africa: impact on heating system design. *Energy Conversion and Management*, *47*, 687–701. https://doi.org/10.1016/j.enconman.2005.06.022.
107. Rasheduzzaman, M., Singh, R., Haas, C. N., & Gurian, P. L. (2020). Required water temperature in hotel plumbing to control Legionella growth. *Water Research*, 182, 115943. https://doi.org/10.1016/j.watres.2020.115943.
108. Rathnayaka, K., Malano, H., Maheepala, S., George, B., Nawarathna, B., Arora, M., & Roberts, P. (2015). Seasonal Demand Dynamics of Residential Water End-Uses. *Water*, 7(1), 202-216. https://doi.org/10.3390/w7010202.
109. Roest, K., Hofman, J., & van Loosdrecht, M. (2010). De Nederlandse watercyclus kan energie opleveren [The Dutch water cycle can generate energy] (in Dutch). *H2O*, 43, 47–51. Available at : https://library.kwrwater.nl/publication/51463220/de-nederlandse-watercyclus-kan-energie-opleveren/.
110. Rohatgi, A. (2024). *WebPlotDigitizer (v 5)*. https://automeris.io/WebPlotDigitizer.
111. Salmanova, F., & Yusupov, I. (2023). The use of solar energy to provide hot water to a rural house and thermal energy analysis of the system. *The Scientific Heritage*, 107. https://doi.org/10.5281/zenodo.7673193
112. Salomons, E., & Housh, M. (2000). Smart Water Meters Can Save Lives During the COVID-19 Pandemic. *Journal of Water Resources Planning and Management*, *148*, 02522003. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001548.
113. Sborz, J., Cominato, C., Kalbusch, A., & Henning, E. (2022). Hourly and daily domestic hot water consumption in social housing dwellings: An analysis in apartment buildings in Southern Brazil. *Solar Energy*, *232*, 459–470. https://doi.org/10.1016/j.solener.2021.12.067.
114. Sborz, J., Kalbusch, A., & Henning, E. (2024). Factors that determine hot and cold-water consumption in social housing apartments. *Architectural Engineering and Design Management*, *20*(6), 1669–1686. https://doi.org/10.1080/17452007.2024.2436941.
115. Schaffer, M., Widén, J., Vera-Valdés, J. E., Marszal-Pomianowska, A., & Larsen, T. S. (2024). Disaggregation of total energy use into space heating and domestic hot

water: A city-scale suited approach. *Energy*, *291*, 130351. https://doi.org/10.1016/j.energy.2024.130351.

116. Schattmann, F. T., Eggert, D., Puknat, R., Niepelt, R., & Institut für Solarenergieforschung. (2025). *Field Data on Heating Energy Demands in Multi-Family Homes in Lower Saxony (1.0.1)* [Data set]. Zenodo. https://doi.org/10.5281/zenodo.17469426
117. Schoenbauer, B., Bohac, D., & Hewett, M. (2012). Measured Residential Hot Water End Use. *ASHRAE Transactions*, *118*(pt. 1), 872–889, CH-12-014.
118. Sousa V., & Meireles I. (2022). Dynamic simulation of the energy consumption and carbon emissions for domestic hot water production in a touristic region. *Journal of Cleaner Production*, *355*, 131828. https://doi.org/10.1016/j.jclepro.2022.131828.
119. Sørensen, Å. L., Walnum H. T., Sartori I., & Andersen I. (2021). Energy flexibility potential of DHW systems in Norwegian apartment buildings: A rule-based approach. *Proceeding of E3S Web Conference - Cold Climate HVAC & Energy 2021*, *246*, 11005.
120. Spanish Ministry of Health. (2022). *Royal Decree 487/2022 establishing sanitary requirements for the prevention and control of legionellosis*. Government of Spain.
121. Spanish Ministry of Transport, Mobility and Urban Agenda (2013). *Technical Building Code (CTE), Basic Document HE: Energy Savings*. Government of Spain.
122. Standards Australia/Standards New Zealand (2021a). *AS/NZS 3500. Plumbing and drainage*. Standards Australia / Standards New Zealand.
123. Standards Australia/Standards New Zealand. (2021b). *AS/NZS 4234:2021 – Heated water systems: Calculation of energy consumption (Standard No. AS/NZS 4234:2021).* Standards Australia / Standards New Zealand.
124. Swedish National Board of Housing, Building and Planning (2015). *Building regulations – hygiene, health and environment (BBR)*. Sweden: Swedish National Board of Housing, Building and Planning.
125. Sullivan, G., & Parker, G. The economics of commercial-grade horizontal-axis clothes washers. *Proceeding of Conserv99 (American Water Works Association)*.
126. Thomas, M., Ceng, T., Hayden, A. C. S., Ceng, R. L. D., & Girigoclu, O. (2011). A New Study of Hot-Water Use in Canada. *ASHRAE Transactions*, *117*(pt. 1), 673–682, LV-11-002.
127. UNE (Spanish Association for Standardization). (2015). *UNE 94002: Water supply systems inside buildings*. UNE.
128. UNI (Italian Organization for Standardization). (2019). UNI/TS 11300-2: *Energy performance of buildings – Part 2: Determination of primary energy need and system efficiency*. UNI.
129. United Nations (2010). *Resolution 64/292: The human right to water and sanitation*. Retrieved 13 October 2018.
130. U.S. Environmental Protection Agency. (2026). *Data and information used by WaterSense*. United States. Retrieved April 1, 2026, from https://www.epa.gov/watersense/data-and-information-used-watersense
131. Verhaert I., Bleys B., Binnemans S., & Janssen E. (2016). A Methodology to Design Domestic Hot Water Production Systems Based on Tap Patterns. *Proceeding of Clima 2016*, Aalborg (DK).

132. Vine E., Diamond R., & Szydlowski R. (1987). Domestic Hot Water Consumption in four Low-Income Apartments Buildings. *Energy*, *12*(6), 459–467. https://doi.org/10.1016/0360-5442(87)90005-3.
133. Vitter, J., & Webber, M. (2018). Water Event Categorization Using Sub-Metered Water and Coincident Electricity Data. *Water*, *10*(6), 714. https://doi.org/10.3390/w10060714.
134. Wang J., Fu G., & Savic D. (2026). Leveraging large language models for automating water distribution network optimization. *Water Research*, *288*, 124536. https://doi.org/10.1016/j.watres.2025.124536.
135. Walnum, H. T., Sørensen, Å. L., & Stråby, K. (2021). Measurement data on domestic hot water consumption and related energy use in hotels, nursing homes and apartment buildings in Norway. *Data in Brief*, *37*, 107228. https://doi.org/10.1016/j.dib.2021.107228.
136. Webster, C. J. D. (1972). An investigation of the use of water outlets in multi-storey flats. *Proceedings of the Symposium on Water Demand in Buildings (CIB Commission)*, Watford (UK).
137. Weihl and Kempton (1985). Residential Hot Water Energy Analysis: Instruments and Algorithms. *Energy & Buildings*, *8*, 197–204. https://doi.org/10.1016/0378-7788(85)90004-0.
138. World Health Organization (2017). *Guidelines for Drinking-water Quality (4th ed.)*. World Health Organization.
139. Widén J., Lundh M., Vassileva I., Dahlquist E., Ellegård K., & Wäckelgård E. (2009). Constructing load profiles for household electricity and hot water from time-use data-Modelling approach and validation. *Energy & Buildings*, *41*, 753–768. https://doi.org/10.1016/j.enbuild.2009.02.013.
140. Zenodo. (2026). Zenodo. https://zenodo.org
141. Zhao Q., Wu W., & Simpson A. R. (2025). Optimising behind-the-meter solar for water distribution systems: impact of network configuration and electricity tariff structure. *Journal of Cleaner Production*, *520*, 146069. https://doi.org/10.1016/j.jclepro.2025.146069.
142. Zuniga-Alvarez, M. A., Agbossou, K., Cardenas, A., Kelouwani, S., & Boulon, L. (2020). Demand response strategy applied to residential electric water heaters using dynamic programming and K-means clustering. *IEEE Transactions on Sustainable Energy*, 11(1), 524–533. https://doi.org/10.1109/TSTE.2019.2897288

Graphical abstract



Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: