CHAPTER 2

Water Demand

2.1 TERMINOLOGY

Water conveyance in a water supply system depends on the rates of production, delivery, consumption and leakage (Figure 2.1).

Water production

Water production (Q_{wp}) takes place at water treatment facilities. It normally has a constant rate that depends on the purification capacity of the treatment installation. The treated water ends up in a clear water reservoir from where it is supplied to the system (Reservoir A in Figure 2.1).

Water delivery

Water delivery (Q_{wd}) starts from the clear water reservoir of the treatment plant. Supplied directly to the distribution network, the generated flow will match certain demand patterns. When the distribution area is located far away from the treatment plant, the water is likely to be transported to another reservoir (B in Figure 2.1) that is usually constructed at the beginning of the distribution network. In principle, this delivery is done at the same constant flow rate that is equal to the water production.

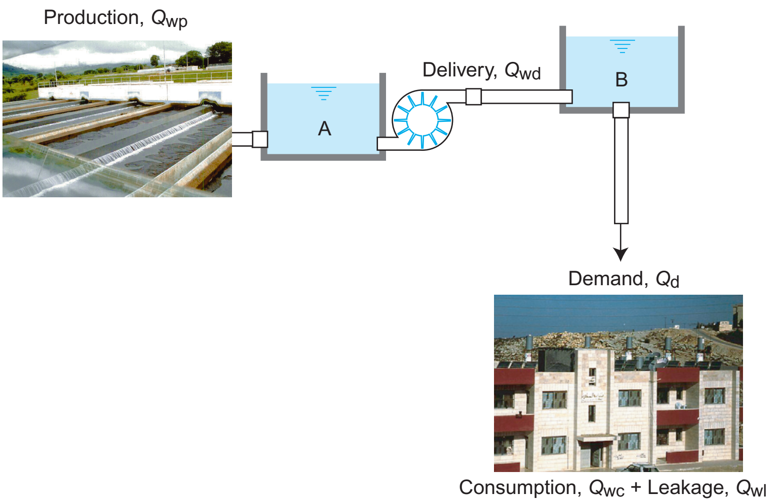


Figure 2.1. Flows in water supply systems.

Water consumption

Water consumption (Q_{wc}) is the quantity directly utilised by the consumers. This generates variable flows in the distribution network caused by many factors: users' needs, climate, source capacity etc.

Water leakage

Water leakage (Q_{wl}) is the amount of water physically lost from the system. The generated flow rate is in this case more or less constant and depends on overall conditions in the system.

Water demand

In theory, the term *water demand* (Q_d) coincides with water consumption. In practice, however, the demand is often monitored at supply points where the measurements include leakage, as well as the quantities used to refill the balancing tanks that may exist in the system. In order to avoid false conclusions, a clear distinction between the measurements at various points of the system should always be made. It is commonly agreed that $Q_d = Q_{wc} + Q_{wl}$. Furthermore, when supply is calculated without having an interim water storage, i.e. water goes directly to the distribution network: $Q_{wd} = Q_d$, otherwise: $Q_{wd} = Q_{wp}$.

Water demand is commonly expressed in cubic meters per hour (m^3/h) or per second (m^3/s), litres per second (l/s), mega litres per day (Ml/d) or litres per capita per day (l/c/d or lpcpd). Typical Imperial units are cubic feet per second (ft^3/s), gallon per minute (gpm) or mega gallon per day (mgd).[1] The mean value derived from annual demand records represents the *average demand*. Divided by the number of consumers, the average demand becomes the *specific demand (unit consumption per capita)*.

Average demand
Specific demand

Apart from neglecting leakage, the demand figures can often be misinterpreted due to lack of information regarding the consumption of various categories. Table 2.1 shows the difference in the level of specific demand depending on what is, or is not, included in the figure. The last two groups in the table coincide with commercial and domestic water use, respectively.

Table 2.1. Water demand in The Netherlands in 2001 (VEWIN).

	Annual (10^6 m^3)	Q_d(l/c/d)[1]
Total water delivered by water companies	1247	214
Drinking water delivered by water companies	1177	202
Drinking water paid for by consumers	1119	192
Consumers below 10,000 m^3/y per connection (metered)	940	161
Consumers below 300 m^3/y per connection (metered)	714	122

[1] Based on total population of approx. 16 million.

[1] A general unit conversion table is given in Appendix 7. See also spreadsheet lesson A5.8.1: 'Flow Conversion' (Appendix 5).

Accurate forecasting of water demand is crucial whilst analysing the hydraulic performance of water distribution systems. Numerous factors affecting the demand are determined from the answers to three basic questions:

1 *For which purpose is the water used?* The demand is affected by a number of consumption categories: domestic, industrial, tourism etc.
2 *Who is the user?* Water use within the same category may vary due to different cultures, education, age, climate, religion, technological process etc.
3 *How valuable is the water?* The water may be used under circumstances that restrict the demand: scarce source (quantity/quality), bad access (no direct connection, fetching from a distance), low income of consumers etc.

Answers to the above questions reflect on the quantities and moments when the water will be used, resulting in a variety of demand patterns. Analysing or predicting these patterns is not always an easy task. Uncritical adoption of other experiences where the field information is lacking is the wrong approach; each case is independent and the conclusions drawn are only valid for local conditions.

Variations in water demand are particularly visible in developing countries where prosperity is predominantly concentrated in a few major, usually overcrowded, cities with peripheral areas often having restricted access to drinking water. These parts of the system will be supplied from public standpipes, individual wells or tankers, which cause substantial differences in consumption levels within the same distribution area. Figure 2.2 shows average specific consumption for a number of large cities in Asia.

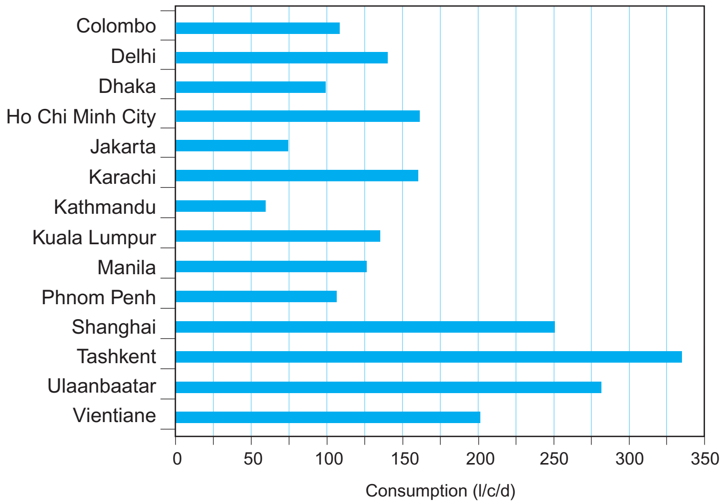


Figure 2.2. Specific consumption in Asian cities (McIntosh, 2003).

Table 2.2. Specific demand around Lake Victoria in Africa (IIED, 2000).

	Piped (l/c/d)	Un-piped (l/c/d)
Average for the entire region	45	22
Average for urban areas (small towns)	65	26
Average for rural areas	59	8
Part of the region in Uganda	44	19
Part of the region in Tanzania	60	24
Part of the region in Kenya	57	21

Comparative figures in Africa are generally lower, resulting from the range of problems that cause intermediate supply, namely long distances, electricity failures, pipe bursts, polluted ground water in deep wells, etc.

A water demand survey was conducted for the region around Lake Victoria, covering parts of Uganda, Tanzania and Kenya. The demand where there is a piped supply (the water is tapped at home) was compared with the demand in un-piped systems (no house connection is available). The results are shown in Table 2.2.

Unaccounted-for water

An unavoidable component of water demand is *unaccounted-for water* (UFW), the water that is supplied 'free of charge'. In quite a lot of transport and distribution systems in developing countries this is the most significant 'consumer' of water, accounting sometimes for over 50% of the total water delivery.

Causes of UFW differ from case to case. Most often it is a leakage that appears due to improper maintenance of the network. Other non-physical losses are related to the water that is supplied and has reached the taps, but is not registered or paid for (under-reading of water meters, illegal connections, washing streets, flushing pipes, etc.)

2.2 CONSUMPTION CATEGORIES

2.2.1 *Water use by various sectors*

Water consumption is initially split into domestic and non-domestic components. The bulk of non-domestic consumption relates to the water used for agriculture, occasionally delivered from integral water supply systems, and for industry and other commercial uses (shops, offices, schools, hospitals, etc.). The ratio between the domestic and non-domestic consumption in The Netherlands in the period 1960–2000 is shown in Figure 2.3.[2]

[2] The domestic consumption in Figure 2.3 is derived from consumers metered below 300 m^3/y per connection. The real consumption is assumed to be slightly higher; the figure assessed by VEWIN for 2001 is 126 l/c/d compared to 134 l/c/d in 1995.

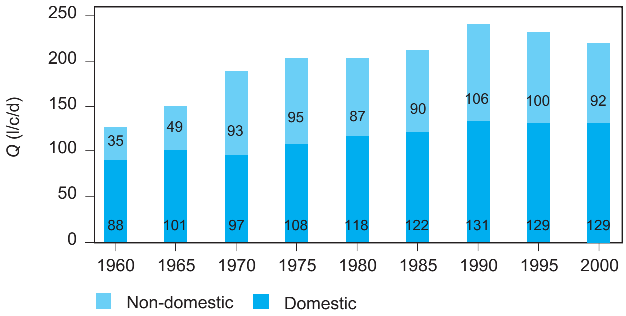


Figure 2.3. Domestic and non-domestic consumption in The Netherlands (VEWIN).

Table 2.3. Domestic vs. non-domestic consumption in some African states (SADC, 1999).

Country	Agriculture (%)	Industry (%)	Domestic (%)
Angola	76	10	14
Botswana	48	20	32
Lesotho	56	22	22
Malawi	86	3	10
Mozambique	89	2	9
South Africa	62	21	17
Zambia	77	7	16
Zimbabwe	79	7	14

In the majority of developing countries, agricultural- and domestic water consumption is predominant compared to the commercial water use, as the example in Table 2.3 shows. However, this water is rarely supplied from an integral system.

In warm climates, the water used for irrigation is generally the major component of total consumption; Figure 2.4 shows an example of some European countries around the Mediterranean Sea: Spain, Italy and Greece. On the other hand, highly industrialised countries use huge quantities of water, often of drinking quality, for cooling; typical examples are Germany, France and Finland, which all use more than 50% of the total consumption for this purpose. Striving for more efficient irrigation methods, industrial processes using alternative sources and recycling water have been and still are a concern in developed countries for the last few decades.

2.2.2 *Domestic consumption*

Domestic water consumption is intended for toilet flushing, bathing and showering, laundry, dishwashing and other less water intensive or less frequent purposes: cooking, drinking, gardening, car washing, etc. The

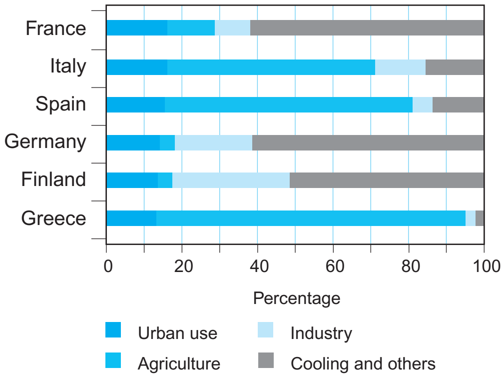


Figure 2.4. Water use in Europe (EEA, 1999).

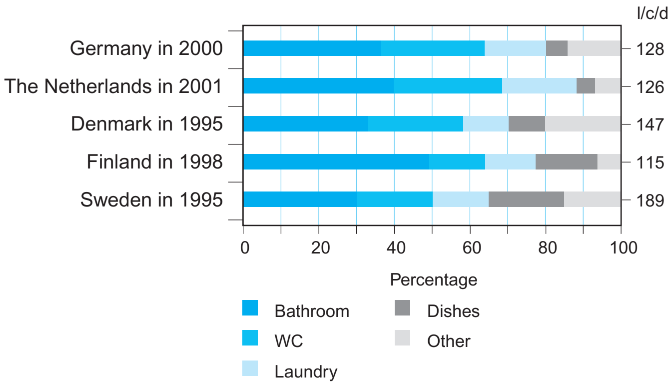


Figure 2.5. Domestic water use in Europe (EEA, BGW, VEWIN).

example in Figure 2.5 shows rather wide variation in the average domestic consumption of some industrialised countries. Nevertheless, in all the cases indicated 50–80% of the total consumption appears to be utilised in bathrooms and toilets.

The habits of different population groups with respect to water use were studied in The Netherlands (Achttienribbe, 1993). Four factors compared were age, income level, household size and region of the country. The results are shown in Figure 2.6.

The figures prove that even with detailed statistics available, conclusions about global trends may be difficult. In general, the consumption is lower in the northern part of the country, which is a less populated, mostly agricultural region. Nonetheless, interesting findings from the graphs are evident: the middle-aged group is the most moderate water user, more frequent toilet use and less frequent shower use is exercised by older groups, larger families are with a lower consumption per capita, etc.

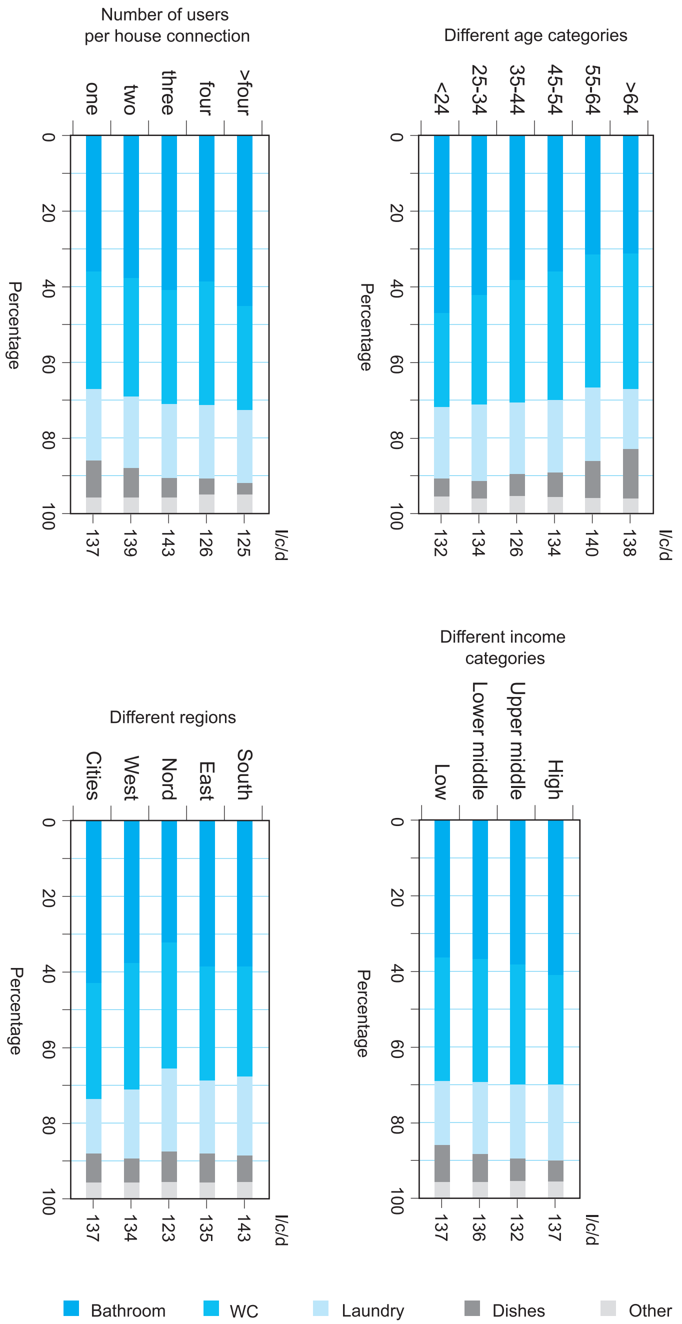


Figure 2.6. Structure of domestic consumption in The Netherlands (Achttienribbe, 1993).

In cases where there is an individual connection to the system, the structure of domestic consumption in water scarce areas may well look similar but the quantity of water used for particular activities will be minimised. Apart from the change of habits, this is also a consequence of low pressures in the system directly affecting the quantities used for showering, gardening, car washing, etc. On top of this, the water company may be forced to ration the supply by introducing regular interruptions. In these situations consumers will normally react by constructing individual tanks. In urban areas where supply with individual tanks takes place, the amounts of water available commonly vary between 50–100 l/c/d.

2.2.3 *Non-domestic consumption*

Non-domestic or commercial water use occurs in industry, agriculture, institutions and offices, tourism, etc. Each of these categories has its specific water requirements.

Industry

Water in industry can be used for various purposes: as a part of the final product, for the maintenance of manufacturing processes (cleaning, flushing, sterilisation, conveying, cooling, etc) and for the personal needs (usually comparatively marginal). The total quantities will largely depend on the type of industry and technological process. They are commonly expressed in litres per unit of product or raw material. Table 2.4 gives an indication for a number of industries; an extensive overview can be found in HR Wallingford (2003).

Table 2.4. Industrial water consumption (Adapted from: HR Wallingford, 2003).

Industry	Litres per unit product
Carbonated soft drinks[1]	1.5–5 per litre
Fruit juices[1]	3–15 per litre
Beer[1]	4–22 per litre
Wine	1–4 per litre
Fresh meat (red)	1.5–9 per kg
Canned vegetables/fruits	2–27 per kg
Bricks	15–30 per kg
Cement	4 per kg
Polyethylene	2.5–10 per kg
Paper[2]	4–35 per kg
Textiles	100–300 per kg
Cars	2500–8000 per car

Notes
[1] Largely dependant on the packaging and cleaning of bottles.
[2] Recycled paper.

Agriculture
Water consumption in agriculture is mainly determined by irrigation and livestock needs. In peri-urban or developed rural areas, this demand may also be supplied from the local distribution system.

The amounts required for irrigation purposes depend on the plant sort, stage of growth, type of irrigation, soil characteristics, climatic conditions, etc. These quantities can be assessed either from records or by simple measurements. A number of methods are available in literature to calculate the consumption based on meteorological data (Blaney-Criddle, Penman, etc.). According to Brouwer and Heibloem (1986), the consumption is unlikely to exceed a monthly mean of 15 mm per day, which is equivalent to 150 m^3/d per hectare. Approximate values per crop are given in Table 2.5.

Water required for livestock depends on the sort and age of the animal, as well as climatic conditions. Size of the stock and type of production also play a role. For example, the water consumption for milking cows is 120–150 l/d per animal, whilst cows typically need only 25 l/d (Brandon, 1984) (see Table 2.6).

Table 2.5. Seasonal crop water needs (Brouwer and Heibloem, 1986).

Crop	Season (days/year)	Consumption (mm/season)
Bananas	300–365	1200–2200
Beans	75–110	300–500
Cabbages	120–140	350–500
Citrus fruit	240–365	900–1200
Corn	80–180	500–800
Potatoes	105–145	500–700
Rice	90–150	450–750
Sunflowers	125–130	600–1000
Tomatoes	135–180	400–800
Wheat	120–150	450–650

Table 2.6. Animal water consumption (Brandon, 1984).

Animal	Litres per day
Cows	25–150
Oxen, horses, etc.	15–40
Pigs	10–30
Sheep, goats	5–6
Turkeys (per 100)	65–70
Chickens (per 100)	25–30
Camels	2–3

Institutions
Commercial consumption in restaurants, shops, schools and other institutions can be assessed as a total supply divided by the number of consumers (employees, pupils, patients, etc.). Accurate figures should be available from local records at water supply companies. Some indications of unit consumption are given in Table 2.7. These assume individual connection with indoor water installations and waterborne sanitation, and are only relevant during working days.

Tourism
Tourist and recreational activities may also have a considerable impact on water demand. The quantities per person (or per bed) per day vary enormously depending on the type and category of accommodation; in luxury hotels, for instance, this demand can go up to 600 l/c/d. Table 2.8 shows average figures in Southwest England.

Miscellaneous groups
Water consumption that does not belong to any of the above-listed groups can be classified as miscellaneous. These are the quantities used for fire fighting, public purposes (washing streets, maintaining green areas, supply for fountains, etc.), maintenance of water and sewage systems (cleansing, flushing mains) or other specific uses (military facilities, sport complexes, zoos, etc.). Sufficient information on water consumption in such cases should be available from local records.

Table 2.7. Water consumption in institutions (adapted from: HR Wallingford, 2003).

Premises	Consumption
Schools	25–75 l/d per pupil
Hospitals	350–500 l/d per bed
Laundries	8[1]–60 litre per kg washing
Small businesses	25 l/d per employee
Retail shops/stores	100–135 l/d per employee
Offices	65 l/d per employee

[1] Recycled water used for rinsing

Table 2.8. Tourist water consumption in Southwest England (Brandon, 1984).

Accommodation	Consumption (l/c/d)
Camping sites	68
Unclassified hotels	113
Guest houses	130
1- and 2-star hotels	168
3-, 4- and 5-star hotels	269

Sometimes this demand is unpredictable and can only be estimated on an empirical or statistical basis. For example, in the case of fire fighting, the water use is not recorded and measurements are difficult because it is not known in advance when and where the water will be needed. Provision for this purpose will be planned with respect to potential risks, which is a matter discussion between the municipality (fire department) and water company.

On average, these consumers do not contribute substantially in overall demand. Very often they are neither metered nor accounted for and thus classified as UFW.

PROBLEM 2.1
A water supply company has delivered an annual quantity of 80,000,000 m^3 to a city of 1.2 million inhabitants. Find out the specific demand in the distribution area. In addition, calculate the domestic consumption per capita with leakage from the system estimated at 15% of the total supply, and billed non-domestic consumption of 20,000,000 m^3/y.

Answer:
Gross specific demand can be determined as:

$$Q_{avg} = \frac{80{,}000{,}000 \times 1000}{1{,}200{,}000/365} \approx 183 \text{ l/c/d}$$

The leakage of 15% of the total supply amounts to an annual loss of 12 million m^3. Reducing the total figure further for the registered non-domestic consumption yields the annual domestic consumption of $80 - 12 - 20 = 48$ million m^3, which is equal to a specific domestic consumption of approx.110 l/c/d.

Self-study:
Workshop problems A1.1.1 and A1.1.2 (Appendix 1)
Spreadsheet lesson A5.8.1 (Appendix 5)

2.3 WATER DEMAND PATTERNS

Each consumption category can be considered not only from the perspective of its average quantities but also with respect to the timetable of when the water is used.

Demand variations are commonly described by the *peak factors*. These are the ratios between the demand at particular moments and the average demand for the observed period (hour, day, week, year, etc.). For example, if the demand registered during a particular hour was 150 m^3

and for the whole day (24 hours) the total demand was 3000 m^3, the average hourly demand of 3000/24 = 125 m^3 would be used to determine the peak factor for the hour, which would be 150/125 = 1.2. Other ways of peak demand representation are either as a percentage of the total demand within a particular period (150 m^3 for the above hour is equal to 5% of the total daily demand of 3000 m^3), or simply as the unit volume per hour (150 m^3/h).

Human activities have periodic characteristics and the same applies to water use. Hence, the average water quantities from the previous paragraph are just indications of total requirements. Equally relevant for the design of water supply systems are consumption peaks that appear during one day, week or year. A combination of these maximum and minimum demands defines the absolute range of flows that are to be delivered by the water company.

Time-wise, we can distinguish the *instantaneous, daily (diurnal), weekly* and *annual (seasonal)* pattern in various areas (home, building, district, town, etc.). The larger the area is, the more diverse the demand pattern will be as it then represents a combination of several consumption categories, including leakage.

2.3.1 *Instantaneous demand*

Simultaneous demand

Instantaneous demand (in some literature *simultaneous demand*) is caused by a small number of consumers during a short period of time: a few seconds or minutes. Assessing this sort of demand is the starting point in building-up the demand pattern of any distribution area. On top of that, the instantaneous demand is directly relevant for network design in small residential areas (tertiary networks and house installations). The demand patterns of such areas are much more unpredictable than the demand patterns generated by larger number of consumers. *The smaller the number of consumers involved, the less predictable the demand pattern will be*.

The following *hypothetical* example illustrates the relation between the peak demands and the number of consumers.

A list of typical domestic water activities with provisional unit quantities utilised during a particular period of time is shown in Table 2.9. Parameter Q_{ins} in the table represents the average flow obtained by dividing the total quantity with the duration of the activity, converted into litres per hour.

Instantaneous flow

For example, activity 'A–Toilet flushing' is in fact refilling of the toilet cistern. In this case there is a volume of 8 l, within say one minute after the toilet has been flushed. In theory, to be able to fulfil this requirement, the pipe that supplies the cistern should allow the flow of $8 \times 60 = 480$ l/h within one minute. This flow is thus needed within a

Table 2.9. Example of domestic unit water consumption.

Activity	Total quantity (litres)	Duration (minutes)	Q_{ins} (l/h)
A – Toilet flushing	8	1	480
B – Showering	50	6	500
C – Hand washing	2	1/2	240
D – Face and teeth	3	1	180
E – Laundry	60	6	600
F – Cooking	15	5	180
G – Dishes	40	6	400
H – Drinking	1/4	1/20	300
I – Other	5	2	150

relatively short period of time and is therefore called the *instantaneous flow*.

Although the exact moment of water use is normally unpredictable, it is well known that there are some periods of the day when it happens more frequently. For most people this is in the morning after they wake-up, in the afternoon when they return from work or school or in the evening before they go to sleep.

Considering a single housing unit, it is not reasonable to assume a situation in which all water-related activities from the above table are executed simultaneously. For example, in the morning, a combination of activities A, B, D and H might be possible. If this is the assumed maximum demand during the day, the maximum instantaneous flow equals the sum of the flows for these four activities. Hence, the pipe that provides water for the house has to be sufficiently large to convey the flow of:

$$480 + 500 + 180 + 300 = 1460 \text{ l/h}$$

Instantaneous peak factor

With an assumed specific consumption of 120 l/c/d and, say, four people living together, the *instantaneous peak factor* will be:

$$pf_{ins} = \frac{1460}{120 \times 4/24} = 73$$

Thus, there was at least one short moment within 24 hours when the instantaneous flow to the house was 73 times higher than the average flow of the day.

Applying the same logic for an apartment building, one can assume that all tenants use the water there in a similar way and at a similar moment, but never in exactly the same way *and* at exactly the same moment. Again, the maximum demand of the building occurs in the morning. This could consist of, for example, toilet flushing in say three apartments, hand washing in two, teeth brushing in six, doing the laundry in two and drinking water in one. The maximum instantaneous flow out of such a consumption scenario case would be:

$$3A + 3B + 2C + 6D + 2E + 1H = 6000 \text{ l/h}$$

which is the capacity that has to be provided by the pipe that supplies the building. Assuming the same specific demand of 120 l/c/d and for possibly 40 occupants, the instantaneous peak factor is:

$$pf_{\text{ins}} = \frac{6000}{120 \times 40/24} = 30$$

Any further increase in the number of consumers will cause the further lowering of the instantaneous peak factor, up to a level where this factor becomes independent from the growth in the number of consumers. As a consequence, some large diameter pipes that have to convey water for possibly 100,000 consumers would probably be designed based on a rather low instantaneous peak factor, which in this example could be 1.4.

Simultaneity diagram

A *simultaneity diagram* can be obtained by plotting the instantaneous peak factors against the corresponding number of consumers. The three points from the above example, interpolated exponentially, will yield the graph shown in Figure 2.7.

In practice, the simultaneity diagrams are determined from a field study for each particular area (town, region or country). Sometimes, a good approximation is achieved by applying mathematical formulae; the equation: $pf_{\text{ins}} \approx 126 \times e^{(-0.9 \times \log N)}$ where N represents the number of consumers, describes the curve in Figure 2.7. Furthermore, the simultaneous

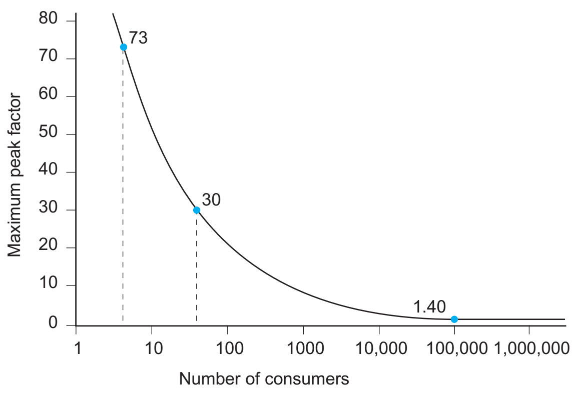


Figure 2.7. Simultaneity diagram (example).

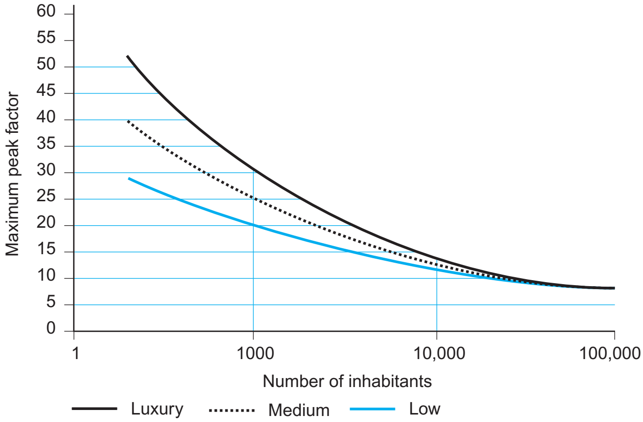


Figure 2.8. Simultaneity diagram of various categories of accommodation.

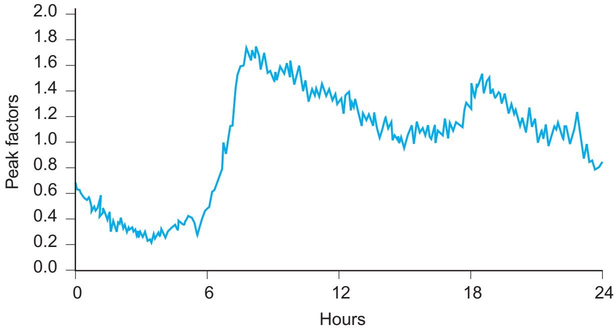


Figure 2.9. Demand pattern in Amsterdam (Municipal Water Company Amsterdam, 2002).

curves can be diversified based on various standards of living i.e. type of accommodation, as Figure 2.8 shows.

In most cases, the demand patterns of more than a few thousand people are fairly predictable. This eventually leads to the conclusion that the water demand of larger group of consumers will, in principle, be evenly spread over a period of time that is longer than a few seconds or minutes. This is illustrated in the 24-hour demand diagram shown in Figure 2.9 for the northern part of Amsterdam. In this example there were nearly 130,000 consumers, and the measurements were executed at 1-minute intervals.

Hourly peak factor

One-hour durations are commonly accepted for practical purposes and the instantaneous peak factor within this period of time will be represented by a single value called the *hourly (or diurnal) peak factor*, as shown in Figure 2.10.

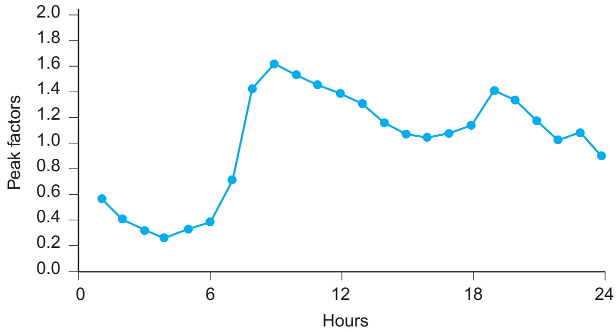


Figure 2.10. Instantaneous demand from Figure 2.9 averaged by the hourly peak factors.

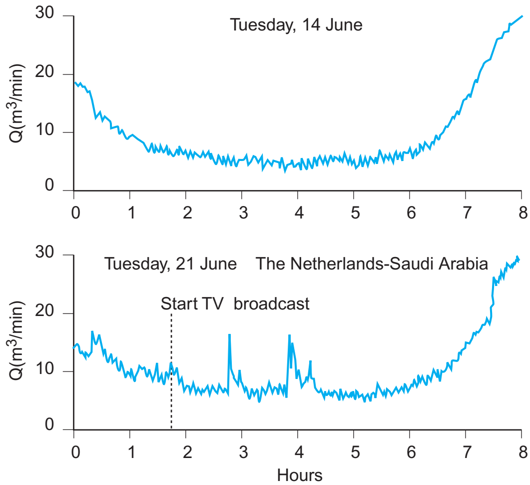


Figure 2.11. Night-time demand during football game (Water Company 'N-W Brabant', NL, 1994).

There are however extraordinary situations when the instantaneous demand may substantially influence the demand pattern, even in the case of large numbers of consumers.

Figures 2.11 and 2.12 show the demand pattern (in m^3/min) during the TV broadcasting of two football matches when the Dutch national team played against Saudi Arabia and Belgium at the 1994 World Cup in the United States of America. The demand was observed in a distribution area of approximately 135,000 people.

The excitement of the viewers is clearly confirmed through the increased water use during the break and at the end of the game, despite the fact that the first match was played in the middle of the night (with different time zones between The Netherlands and USA). Both graphs point almost precisely to the start of the TV broadcast that happened at 01:50 and 18:50, respectively. The water demand dropped soon after the start of the game until the half time when the first peak occurs; it is not difficult to guess for what purpose the water was used! The upper curves

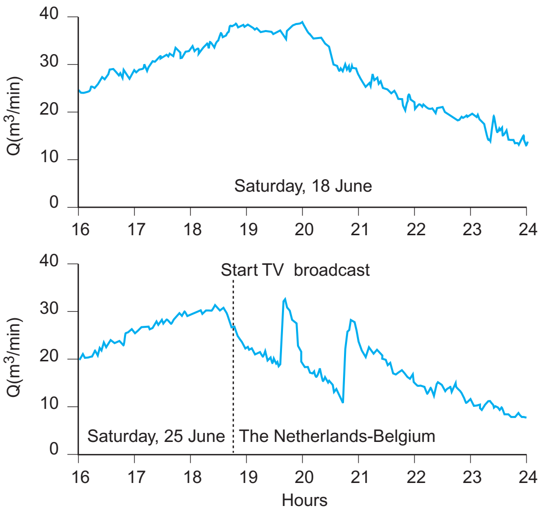


Figure 2.12. Evening demand during football game (Water Company 'N-W Brabant', NL, 1994).

in both figures show the demand under normal conditions, one week before the game at the same period of the day.

This phenomenon is not only typical in The Netherlands; it will be met virtually everywhere where football is sufficiently popular. Its consequence is a temporary drop of pressure in the system while in the most extreme situations a pump failure might occur. Nevertheless, these demand peaks are rarely considered as design parameters and adjusting operational settings of the pumps can easily solve this problem.

PROBLEM 2.2

In a residential area of 10,000 inhabitants, the specific water demand is estimated at 100 l/c/d (leakage included). During a football game shown on the local TV station, the water meter in the area registered the maximum flow of 24 l/s, which was 60% above the regular use for that period of the day. What was the instantaneous peak factor in that case? What would be the regular peak factor on a day without a televised football broadcast?

Answers:

In order to calculate the peak factors, the average demand in the area has to be brought to the same units as the peak flows. Thus, the average flow becomes:

$$Q_{avg} = \frac{10{,}000 \times 100}{24/3600} \approx 12 \text{ l/s}$$

The regular peak flow at a particular point of the day is 60% lower than the one registered during the football game, which is 24/1.6 = 15 l/s.

Finally, the corresponding peak factors will be 24/12 = 2 during the football game, and 15/12 = 1.25 in normal supply situations.

Self-study:
Workshop problems A1.1.3–A1.1.5 (Appendix 1)

2.3.2 *Diurnal patterns*

Diurnal demand diagram

For sufficiently large group of consumers, the instantaneous demand pattern for 24-hour period converts into a *diurnal (daily) demand diagram*. Diurnal diagrams are important for the design of primary and secondary networks, and in particular their reservoirs and pumping stations. Being the shortest cycle of water use, a one-day period implies a synchronised operation of the system components with similar supply conditions occurring every 24 hours.

The demand patterns are usually registered by monitoring flows at delivery points (treatment plants) or points in the network (pressure boosting stations, reservoirs, control points with either permanent or temporary measuring equipment). With properly organised measurements the patterns can also be observed at the consumers' premises. First, such an approach allows the separation of various consumption categories and second, the leakage in the distribution system will be excluded, resulting in a genuine consumption pattern.

A few examples of diagrams for different daily demand categories are given in Figures 2.13–2.16.

A flat daily demand pattern reflects the combination of impacts from the following factors:
– large distribution area,
– high industrial demand,
– high leakage level,
– scarce supply (individual storage).

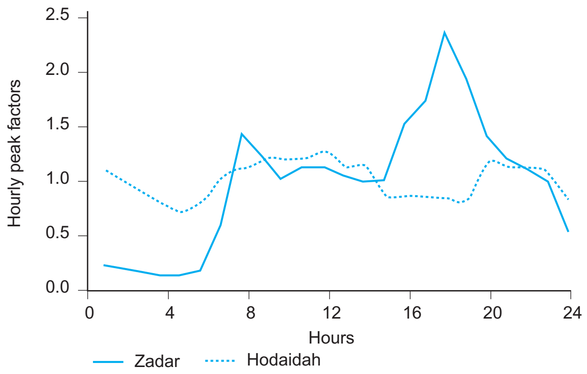


Figure 2.13. Urban demand pattern (adapted from: Gabrić, 1996 and Trifunović, 1993).

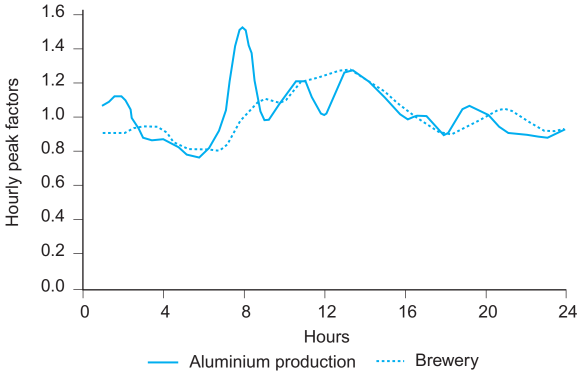


Figure 2.14. Industrial demand pattern – example from Bosnia and Herzegovina (Obradović, 1991).

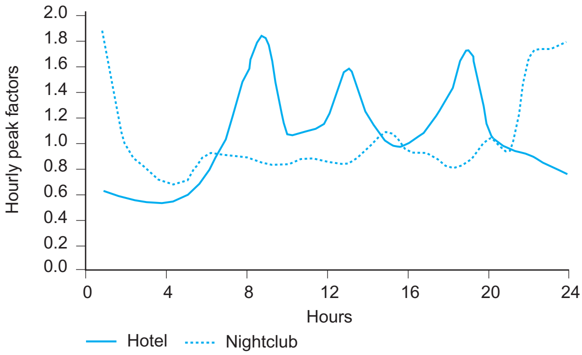


Figure 2.15. Tourist demand pattern – example from Croatia (Obradović, 1991).

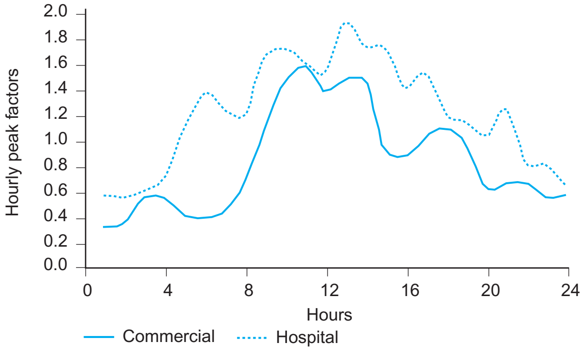


Figure 2.16. Commercial/ institutional demand pattern – example from USA (Obradović, 1991).

Commonly, the structure of the demand pattern in urban areas looks as shown in Figure 2.17: the domestic category will have the most visible variation of consumption throughout the day, industry and institutions will usually work in daily shifts, and the remaining categories, including leakage, are practically constant.

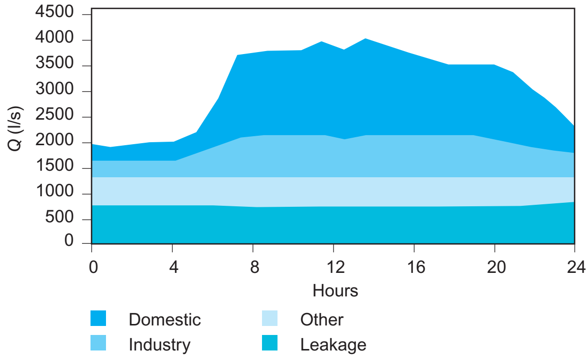


Figure 2.17. Typical structure of diurnal demand in urban areas.

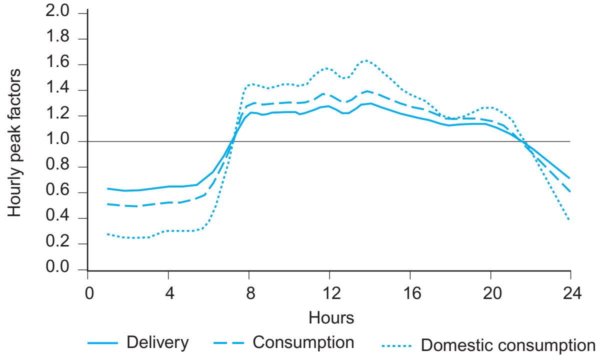


Figure 2.18. Peak factor diagrams of various categories from Figure 2.17.

By separating the categories, the graph will look like Figure 2.18, with peak factors calculated for the domestic consumption only, then for the total consumption (excluding leakage), and finally for the total demand (consumption plus leakage). It clearly shows that contributions from the industrial consumption and leakage flatten the patterns.

2.3.3 *Periodic variations*

The peak factors from diurnal diagrams are derived on the basis of average consumption during 24 hours. This average is subject to two additional cycles: weekly and annual.

Weekly demand pattern

Weekly demand pattern is influenced by average consumption on working and non-working days. Public holidays, sport events, etc. play a role in this case as well. One example of the demand variations during a week is shown in Figure 2.19. The difference between the two curves in this diagram reflects the successful implementation of the leak detection programme.

Consumption in urban areas of Western Europe is normally lower over weekends. On Saturdays and Sundays people rest, which may differ in

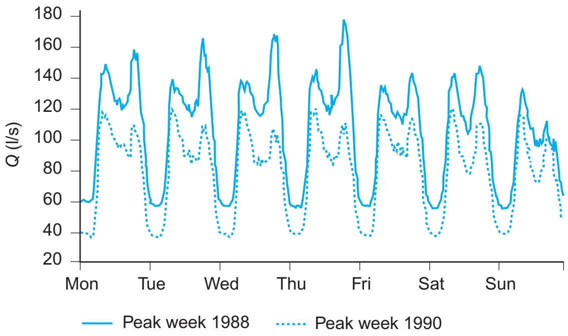


Figure 2.19. Weekly demand variations – Alvington, UK (Dovey and Rogers, 1993).

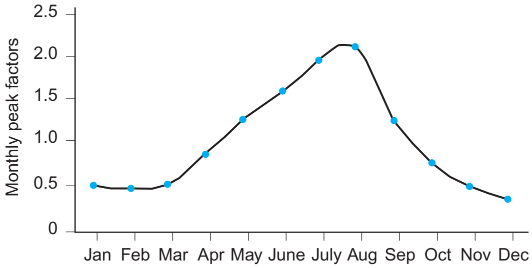


Figure 2.20. Seasonal demand variation in a sea resort (Obradović, 1991).

other parts of the world. For instance, Friday is a non-working day in Islamic countries and domestic consumption usually increases then.

Seasonal variations

Annual variations in water use are predominantly linked to the change of seasons and are therefore also called *seasonal variations*.

The unit consumption per capita normally grows during hot seasons but the increase in total demand may also result from a temporarily increased number of consumers, which is typical for holiday resorts. Figure 2.20 shows the annual pattern in Istria, Croatia on the Adriatic coast; the peaks of the tourist season, during July and August, are also the peaks in water use.

Just as with diurnal patterns, typical weekly and annual patterns can also be expressed through peak factor diagrams. Figure 2.21 shows an example in which the peak daily demand appears typically on Mondays and is 14% above the average, while the minimum on Sundays is 14% below the average daily demand for the week. The second curve shows the difference in demand between summer and winter months, fluctuating within a margin of 10%.

Maximum consumption day

Generalising such trends leads to the conclusion that the absolute peak consumption during one year occurs on a day of the week, and in the month when the consumption is statistically the highest. This day is commonly called the *maximum consumption day*. In the above example, the

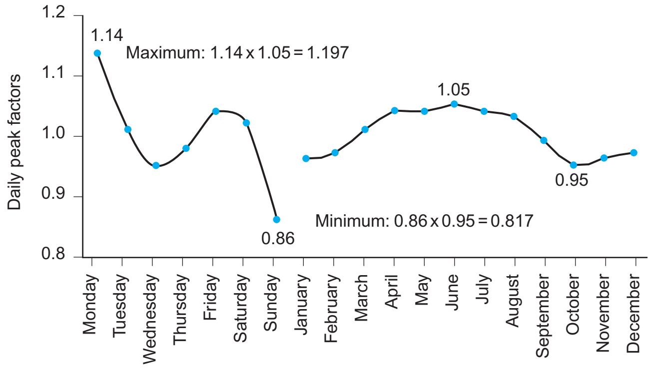


Figure 2.21. Weekly and monthly peak factor diagrams.

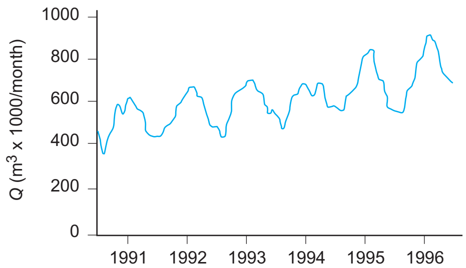


Figure 2.22. Annual demand patterns in Ramallah, Palestine (Thaher, 1998).

maximum consumption day would be a Monday somewhere in June, with its consumption being $1.14 \times 1.05 = 1.197$ times higher than the average daily consumption for the year. In practice however, the maximum consumption day in one distribution area will be determined from the daily demand records of the water company. This is simply the day when the total registered demand was the highest in a particular year.

Finally, the daily, weekly and annual cycles are never repeated in exactly the same way. However, for design purposes a sufficient accuracy is achieved if it is assumed that all water needs are satisfied in a similar schedule during one day, week or year. Regarding the seasonal variations, the example in Figure 2.22 confirms this; the annual patterns in the graph are more or less the same while the average demand grows each year as a result of population growth.

PROBLEM 2.3

A water supply company delivered an annual quantity of 10,000,000 m^3, assuming an average leakage of 20%. On the maximum consumption day, the registered delivery was as follows:

Hour	1	2	3	4	5	6	7	8	9	10	11	12
m^3	989	945	902	727	844	1164	1571	1600	1775	1964	2066	2110
Hour	13	14	15	16	17	18	19	20	21	22	23	24
m^3	1600	1309	1091	945	1062	1455	1745	2139	2110	2037	1746	1018

Determine:

a diurnal peak factors for the area,
b the maximum seasonal variation factor,
c diurnal consumption factors.

Answers:

a From the above table, the average consumption on the maximum consumption day was 1454.75 m^3/h leading to the following hourly peak factors:

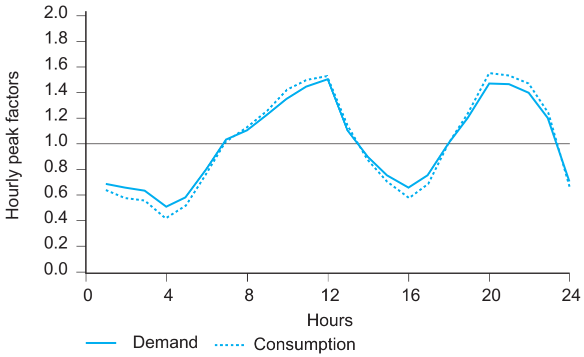
Hour	1	2	3	4	5	6	7	8	9	10	11	12
pf_h	0.680	0.650	0.620	0.500	0.580	0.800	1.080	1.100	1.220	1.350	1.420	1.450
Hour	13	14	15	16	17	18	19	20	21	22	23	24
pf_h	1.100	0.900	0.750	0.650	0.730	1.000	1.200	1.470	1.450	1.400	1.200	0.700

b The average consumption, based on the annual figure, is 10,000,000/365/24 = 1141.55 m^3/h. The seasonal variation factor is therefore 1454.75/1141.55 = 1.274.

c The average leakage of 20% assumes an hourly flow of approx. 228 m^3/h, which is included in the above hourly flows as water loss. The peak factors for consumption will therefore be recalculated without this figure, as the following table shows:

Hour	1	2	3	4	5	6	7	8	9	10	11	12
m^3	761	717	674	499	616	936	1343	1372	1547	1736	1838	1882
pf_h	0.620	0.584	0.549	0.407	0.502	0.763	1.095	1.118	1.261	1.415	1.498	1.534
Hour	13	14	15	16	17	18	19	20	21	22	23	24
m^3	1372	1081	863	717	834	1227	1517	1911	1882	1809	1518	790
pf_h	1.118	0.881	0.703	0.584	0.680	1.000	1.237	1.558	1.534	1.475	1.237	0.644

The diagram of the hourly peak factors for the two situations will look as follows:



Self-study:
Workshop problems A1.1.6 and A1.1.8 (Appendix 1)
Spreadsheet lessons A5.8.2–A5.8.4 (Appendix 5)

2.4 DEMAND CALCULATION

Knowing the daily patterns and periodical variations, the demand flow can be calculated from the following formula:

$$Q_d = \frac{Q_{wc,avg} \times pf_o}{(1 - l/100) \times f_c} \tag{2.1}$$

The definition of the parameters is as follows: Q_d is the water demand of a certain area at a certain moment, $Q_{wc,avg}$ the average water consumption in the area, pf_o the overall peak factor (this is a combination of the peak factor values from the daily, weekly and annual diagrams: $pf_o = pf_h \times pf_d \times pf_m$; the daily and monthly peak factors are normally integrated into one (seasonal) peak factor: $pf_s = pf_d \times pf_m$), l the leakage expressed as a percentage of the water production and f_c the unit conversion factor.

The main advantage of Equation 2.1 is its simplicity although some inaccuracy will be necessarily introduced. Using this formula, the volume of leakage increases with higher consumption i.e. the peak factor value, despite the fixed leakage percentage. For example, if $Q_{wc,avg} = 1$ (regardless of the flow units), $pf_o = 1$ and the leakage percentage is 50%, then as a result $Q_d = 2$. Thus, half of the supply is consumed and the other half is leaked.

If $pf_o = 2$, $Q_d = 4$. Again, this is 'fifty-fifty' but this time the volume of leakage has grown from 1 to 2, which implies its dependence on the consumption level. This is not true as the leakage level is usually constant throughout the day, with a slight increase over night when the pressures in the network are generally higher (already shown in Figure 2.17). Hence, *the leakage level is pressure dependent rather than consumption dependant*.

Nonetheless, the above inaccuracy effectively adds safety to the design. Where this is deemed unnecessary, an alternative approach is suggested, especially for distribution areas with high leakage percentages:

$$Q_d = (Q_{wc,avg} \times pf_o + Q_{wl})\frac{1}{f_c} \tag{2.2}$$

where:

$$Q_{wl} = \frac{l}{100} \times Q_{wp} \tag{2.3}$$

In the case of $pf_o = 1$, demand equals production and assuming the same units for all parameters ($f_c = 1$):

$$Q_{wp} = Q_{wc,avg} + \frac{l}{100} \times Q_{wp} \tag{2.4}$$

This can be re-written as:

$$Q_{wp} = \frac{Q_{wc,avg}}{(1 - l/100)} \tag{2.5}$$

By plugging Equation 2.5 into 2.3 and then to 2.2, the formula for water demand calculation evolves into its final form:

$$Q_d = \frac{Q_{wc,avg}}{f_c} \times \left(pf_o + \frac{l}{100 - l}\right) \tag{2.6}$$

Where reliable information resulting from individual metering of consumers is not available, the average water consumption, $Q_{wc,avg}$, can be approximated in several ways:

$$Q_{wc,avg} = ncq \tag{2.7}$$

$$Q_{wc,avg} = dAcq \tag{2.8}$$

$$Q_{wc,avg} = Acq_a \tag{2.9}$$

$$Q_{wc,avg} = n_u q_u \tag{2.10}$$

where n is the number of inhabitants in the distribution area, c coverage of the area. It can happen that some of the inhabitants are not connected to the system, or some parts of the area are not inhabited. This factor, which has a value of between 0 and 1, converts the number of inhabitants into the number of consumers. q is the specific consumption (l/c/d), d the population density (number of inhabitants per unit surface area), A the surface area of the distribution area, q_a the consumption registered per unit surface area, n_u the production capacity (it represents a number of units (kg, l, pieces, etc.) produced within a certain period), q_u the water consumption per unit product.

Unit consumptions, q, q_a, and q_u, are elaborated in Paragraph 2.2. The data for n, c, d, A and n_u are usually available from statistics or set by planning: local, urban, regional, etc.

As already mentioned, the demand in large urban areas is often composed of several consumption categories. More accuracy in the calculation of demand for water is therefore achieved if the distribution area is split into a number of sub-areas or districts, with standardised categories of water users and a range of consumptions based on local experience.

The average consumption per district can then be calculated from Equation 2.9, which has been modified:

$$Q_{\text{wc,avg}} = A\sum_{i=1}^{n}(q_{\text{a},i}p_i c_i) \tag{2.11}$$

where A is the surface area of the district, n the number of consumption categories within the district, $q_{\text{a},i}$ the unit consumption per surface area of category i, p_i the percentage of the district territory occupied by category i, c_i the coverage within the district territory occupied by category i. With a known population density in each district, the result can be converted into specific demand (per capita).

Regarding the pf_o values, the following are typical combinations:

1 $pf_\text{h} = 1$, $pf_\text{s} = 1$; Q_d represents the average consumption per day. This demand is the absolute average, usually obtained from annual demand records and converted into required flow units.
2 $pf_\text{h} = 1$, $pf_\text{s} = \max$; Q_d represents the average demand during the maximum consumption day.
3 $pf_\text{h} = \max$, $pf_\text{s} = \max$; Q_d is the demand at the maximum consumption hour on the maximum consumption day.
4 $pf_\text{h} = \min$, $pf_\text{s} = \min$; Q_d is the demand at the minimum consumption hour on the minimum consumption day.

The entire range of demands that appear in one distribution system during one year is specified by the demands under 3 and 4, which are shown in Figure 2.23. These peak demands are relevant as parameters for the design of all system components: pipes, pumps and storage.

PROBLEM 2.4

A water supply company in a town with a total population of approx. 275,000 conducted a water demand survey resulting in the following

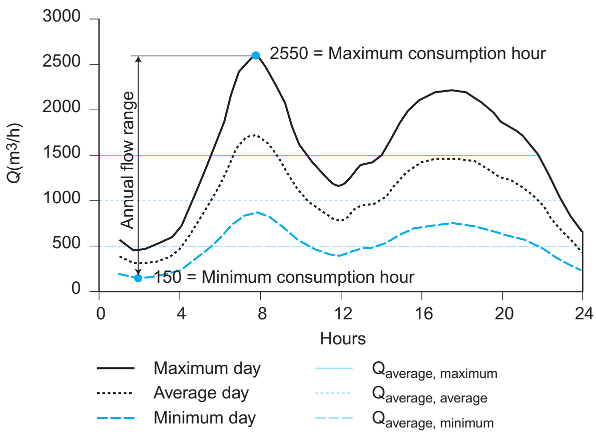


Figure 2.23. Hypothetical annual range of flows in a distribution system.

categories of water users:

Category of water users	q_a (m³/d/ha)
A Residential area, apartments	90
B Residential area, individual houses	55
C Shopping areas	125
D Offices	80
E Schools, Colleges	100
F Hospitals	160
G Hotels	150
H Public green areas	15

The city is divided into 8 districts, each with a known population, contribution to demand from each of the categories, and estimated coverage by the distribution system, as shown in the table below.

Districts		A	B	C	D	E	F	G	H
86,251	p_1(%)	37	23	10	0	4	0	0	26
A_1=250 ha	c_1(%)	100	100	100	0	100	0	0	40
74,261	p_2(%)	20	5	28	11	12	0	5	19
A_2=185 ha	c_2(%)	100	100	95	100	100	0	100	80
18,542	p_3(%)	10	18	3	0	0	42	0	27
A_3=57 ha	c_3(%)	100	100	100	0	0	100	0	35
42,149	p_4(%)	25	28	20	2	15	0	0	10
A_4=88 ha	c_4(%)	100	100	95	100	100	0	0	36
22,156	p_5(%)	50	0	11	0	10	0	0	29
A_5=54 ha	c_5(%)	100	0	100	0	100	0	0	65
9958	p_6(%)	24	11	13	15	13	8	0	16
A_6=29 ha	c_6(%)	100	100	100	100	100	100	0	35
8517	p_7(%)	22	28	8	19	6	0	10	7
A_7=17 ha	c_7(%)	100	100	100	100	100	0	100	50
12,560	p_8(%)	0	0	0	0	55	20	15	10
A_8=16 ha	c_8(%)	0	0	0	0	85	100	100	45

Determine the total average demand of the city.

Answer:
Based on Equation 2.11, a sample calculation of the demand for district 1 will be as follows:

$$
\begin{aligned}
Q_{1,\text{avg}} &= A\sum_{i=1}^{5}(q_{a,i}p_ic_i) \\
&= 250 \times (90 \times 0.37 + 55 \times 0.23 + 125 \times 0.1 \\
&\quad + 100 \times 0.04 + 15 \times 0.26 \times 0.40) \\
&= 666.77\ \text{m}^3/\text{h}
\end{aligned}
$$

The remainder of the results are shown in the table below. The specific demand has been calculated based on the registered population in each district.

	Q_{avg}(m^3/h)	Population	Q_{avg}(l/c/d)
District 1	666.67	86,251	186
District 2	651.97	74,261	211
District 3	216.76	18,542	281
District 4	288.90	42,149	165
District 5	161.05	22,156	174
District 6	99.74	9958	240
District 7	58.03	8517	164
District 8	67.95	12,560	130
Total	2211.16	274,394	193

Self-study:
Spreadsheet lesson A5.8.5–A5.8.7 (Appendix 5)

2.5 DEMAND FORECASTING

Water demand usually grows unpredictably as it depends on many parameters that have their own unpredictable trends. Figure 2.24 illustrates how the rate of increase in consumption may differ even in countries from the same region and with a similar level of economic development.

The experience from Germany proves again how uncertain the forecast can be. Figure 2.25 shows the development of domestic consumption in the period 1970–2000. The forecast made by experts in the Seventies and the Eighties was that the demand in the year 2000 would

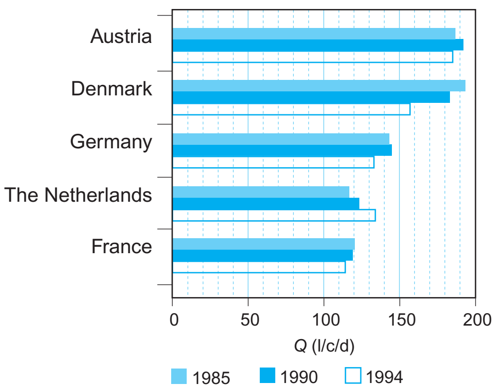


Figure 2.24. Domestic consumption increase in some European countries (EEA, 2001).

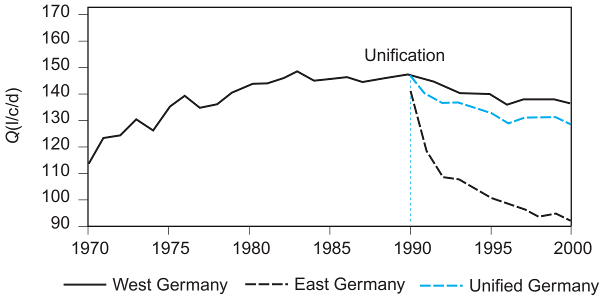


Figure 2.25. Domestic consumption increase in Germany (BGW).

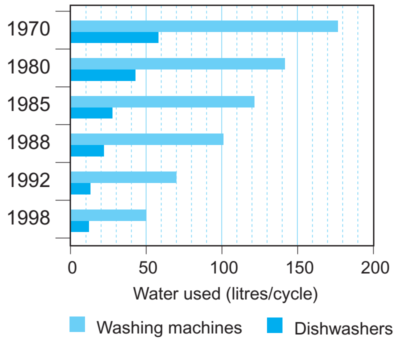


Figure 2.26. Water consumption of washing appliances in Europe (EEA, 2001).

grow to as much as 220 l/c/d, while in reality it fell to approximately 140 l/c/d.

Awareness for the environment in the last decade, combined with low population growth, caused a drop in domestic water use in many countries of Western Europe. In addition, lots of home appliances (i.e. shower heads, taps, washing machines, dishwashers, etc.) have been replaced with more advanced models, able to achieve the same effect with less water (see Figure 2.26). Finally, industry has been moving towards alternative water-saving production technologies, positively influencing the overall water demand. This is unfortunately not the case in many developing countries, where the population growth is much higher, consumers' attitude towards water conservation is comparatively low, and outdated technologies and equipment are still widely used.

Apart from monitoring technological developments, several other assessments must be taken into account while estimating future demand:

- historical demand growth trends,
- projection-based on per capita consumption and population growth trends for domestic category,
- forecast-based on assessment of growth trends of other main consumer categories (industry, tourism, etc.).

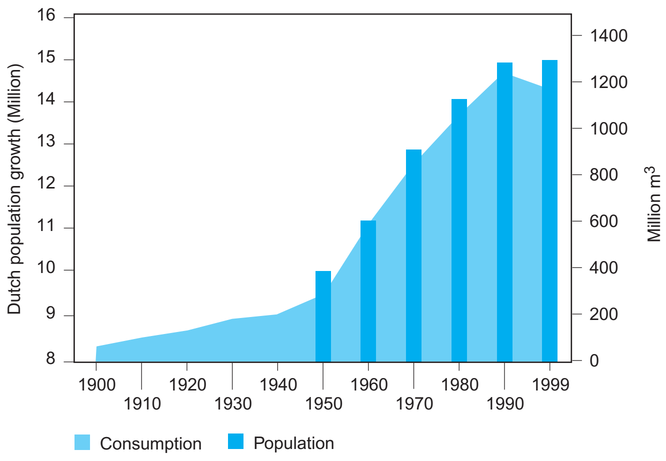


Figure 2.27. Population and demand growth in The Netherlands (VROM).

When combined, all these projections can yield several possible scenarios of consumption growth. While thinking, for instance, about population growth, which is for many developing countries still the major factor in an increase in water demand, useful conclusions can be drawn if the composition of the existing population, fertility and mortality rates, and particularly the rate of migration, can be assessed. That the population and demand growth match reasonably well in general is shown by the example in Figure 2.27.

Two models are commonly used for demand forecast: linear and exponential.
Linear model

$$Q_{i+n} = Q_i\left(1 + n\frac{a}{100}\right) \tag{2.12}$$

Exponential model

$$Q_{i+n} = Q_i\left(1 + \frac{a}{100}\right)^n \tag{2.13}$$

In the above equations Q_i is the water demand at year i, Q_{i+n} the forecast water demand after n years, n the design period, a the average annual population growth during the design period (%).

Which of the models will be more suitable will depend on the conclusions from the above-mentioned analyses. These are to be reviewed periodically, as trends can change within a matter of years.

Figure 2.28 shows the annual demand in The Netherlands in the period 1955–1995. In the first part of this period, up until 1970, the

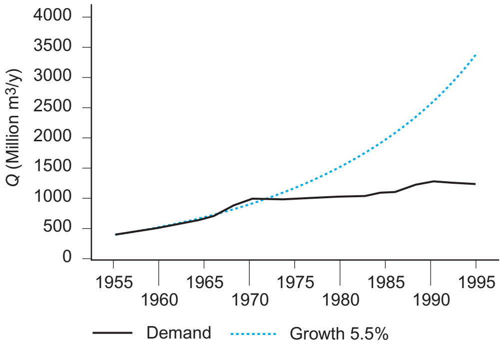


Figure 2.28. Consumption growth in The Netherlands according to the exponential model.

exponential model with an average annual growth of 5.5% (a in Equation 2.13 = 5.5) matches the real demand very closely. However, keeping it unchanged for the entire period would show demand almost three times higher than was actually registered in 1995.

PROBLEM 2.5

In a residential area of 250,000 inhabitants, the specific water demand is estimated at 150 l/c/d, which includes leakage. Calculate the demand in 20 years' time if the assumed annual demand growth is 2.5%. Compare the results by applying the linear and exponential models.

Answers:

The present demand in the city is equal to:

$$Q_{avg} = \frac{250{,}000 \times 150 \times 365}{1000} = 13{,}687{,}500 \text{ m}^3\text{/y}$$

Applying the linear model, the demand after 20 years will grow to:

$$Q_{21} = 13{,}687{,}500\left(1 + 20\frac{2.5}{100}\right) = 20{,}531{,}250 \text{ m}^3\text{/y}$$

which is an increase of 50% compared to the present demand. In the case of the exponential model:

$$Q_{21} = 13{,}687{,}500\left(1 + \frac{2.5}{100}\right)^{20} \approx 22{,}428{,}600 \text{ m}^3\text{/y}$$

which is an increase of approximately 64% compared to the present demand.

Self-study:

Workshop problems A1.1.9 and A1.1.10 (Appendix 1)

Spreadsheet lesson A5.8.8 (Appendix 5)

2.6 DEMAND FREQUENCY DISTRIBUTION

A water supply system is generally designed to provide the demand at guaranteed minimum pressures, for 24 hours a day and 365 days per year. Nevertheless, if the pressure threshold is set high, such a level of service may require exorbitant investment that is actually non-affordable for the water company and consumers. It is therefore useful to analyse how often the maximum peak demands occur during the year. The following example explains the principle.

Knowing both a typical diurnal peak factor diagram (such as the one shown in Figure 2.29) and the range of seasonal peak factors allows for integration of the two. The hourly peak factors corrected by the seasonal peak factors will result in the annual range of the hourly peak hours (Figure 2.30). These are absolute values that refer to the average hour of the average consumption day (Figure 2.31). Consequently, each hour of the year (total 24 × 365) will have a unique peak factor value assigned to it.

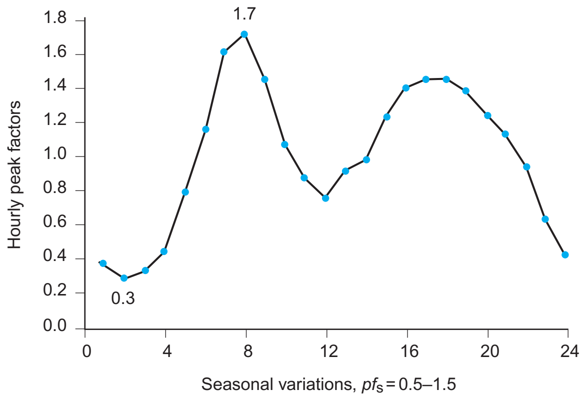


Figure 2.29. Example of a typical diurnal demand pattern.

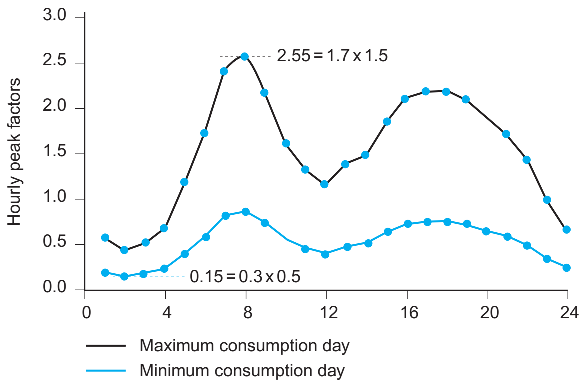


Figure 2.30. Example of the annual range of the peak factors.

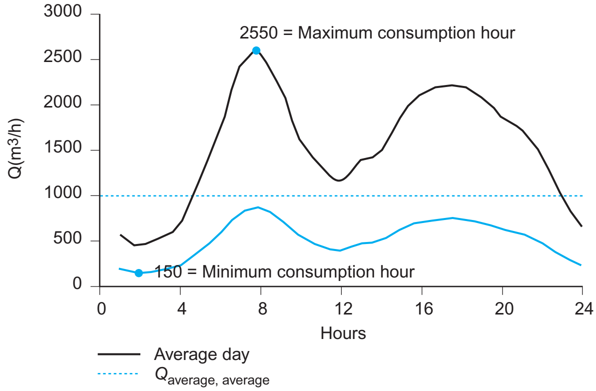


Figure 2.31. Example of the annual range of hourly demands.

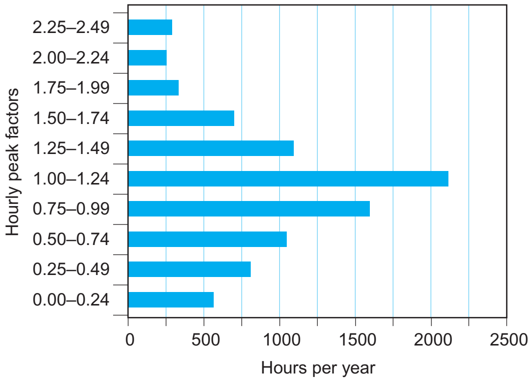


Figure 2.32. Frequency distribution of the diurnal peak factors.

Applying this logic, the diagram with the frequency distribution of all hourly peak factors can be plotted, as the example in Figure 2.32 shows. Converting this diagram into a cumulative frequency distribution curve helps to determine the number of hours in the year when the peak factors exceed the corresponding value. This is illustrated in Figure 2.33, which for instance shows that the peak factors above 2.0 only appear during some 500 hours or approximately 5% of the year. In theory, excluding this fraction from the design considerations would eventually create savings based on a 20% reduction of the system capacity. The consequence of such a choice would be the occasional drop of pressure below the threshold, which the consumers might consider acceptable during a limited period of time.

In practice, the decision about the design peak factor results from the comparison between the costs and benefits. Indeed, it seems rather inefficient to lay pipes that will be used for 80% of their capacity for less than 5% of the total time. However, where there is a considerable scope for energy savings from daily use by lowering the energy losses on a

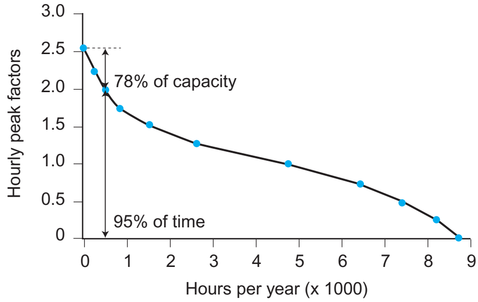


Figure 2.33. Cumulative frequency distribution of the diurnal peak factors.

wider scale, such a choice may look reasonable. Moreover, careful assessment of the network reliability could justify the laying of pipes with reserve capacity that could be utilised during irregular supply situations. Finally, some spare capacity is also useful for practical reasons since it can postpone the construction of phased extensions to expand the system.

The relation between demand for water and hydraulic losses is thoroughly discussed in the following chapter.

Self-study:
Spreadsheet lesson A5.8.9 (Appendix 5).