Mortality and Hardness of Local Water-Supplies

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Summary: In the sixty-one county boroughs of England and Wales with population 80,000 or over in 1961, the harder the local drinking-water and the more calcium it contained the lower was the death-rate in middle and early old age; this was particularly so for cardiovascular and, to a lesser extent, bronchitis mortality, confirming findings relating to the period around 1951. No evidence was obtained that water hardness was reflecting some other environmental factor. A multiple regression study showed that water calcium makes a substantial and highly significant contribution to the variance of the cardiovascular death-rate, between the sixty-one towns, after allowing for environmental factors. Chemical studies of trace elements in water from consumers' taps showed none at a concentration which could be considered toxic either in towns with very soft or with very hard water. Apart from the main minerals—calcium, magnesium, and sodium—only six elements showed consistent differences between the soft and hard waters—manganese and aluminium (higher concentrations in soft waters), and boron, iodine, fluorine, and silica (higher concentrations a hard waters). There is no acceptable explanation at present for the associations found between water hardness and mortality. There is, however, urgent need for incidence and prevalence studies, and detailed investigation of the problem by chemists.

Introduction

Epidemiological studies in several countries have shown that death-rates from cardiovascular disease are higher in areas with soft than in areas with hard drinking water (Kobayashi 1957, Schroeder 1960a and b, 1966, Morris, Crawford, and Heady 1961, 1962, Biorck et al. 1965). In the eighty-three county boroughs of England and Wales there were highly significant negative correlations between cardiovascular mortality (1948-54, the "1951 series" in middle age and contemporary estimates of both total hardness and calcium content of local drinking-water, the lower the death-rate. No such associations were found for other causes of death, apart from bronchitis for which the correlations were lower). In spite of an extensive search, no social or other environmental factor associated with water hardness was found that might "explain" these findings (Morris, Crawford, and Heady 1961, 1962).

Material

A further study (the "1961 series") has now been made in the sixty-one county boroughs of England and Wales with a total population of 80,000 or over at the 1961 Census; the smaller county boroughs were excluded to reduce error in estimates of the death-rates due to small numbers. The data consist of 7 years' mortality, 1958-64, using cause-of-death groupings from the Registrar General's Abridged List, for men and women aged 45-64 and 65-74. A wide range of social indices for each town was also assembled, mainly from the 1961 Census. Chemical analyses of water as drunk locally (i.e., after any chemical treatment of the supply) were obtained for each town, including estimations of calcium (as Ca^{++} magnesium (as Mg^{++} and sodium (as Na^{+}). Average values of hardness and of the main minerals were calculated for each town; where there was more than one supply in a town these were weighted by the proportion of the population served to give a weighted figure.

Results

Table I shows the correlations between water hardness and mortality for all sizeable causes of death in middle and early old age (the product moment correlation coefficient is used throughout as a measure of association). There are again highly significant negative correlations with deaths from all causes in the 4 sex and age groups studied—i.e., the softer the water the higher the death-rate. Correlations with death-rates from cardiovascular disease, which constitute over a third of total mortality in both the male and female groups, are the highest; mortality in the components of the group—cerebrovascular, coronary, and other heart-disease—is also highly associated with water hardness. Correlations with "all causes less cardiovascular disease" are substantially lower, but in contrast to the 1951 series (Morris, Crawford, and Heady 1961) the coefficients are significantly different from zero.

TABLE I—ASSOCIATIONS BETWEEN WATER HARDNESS (1961) AND LOCAL DEATH-RATES (1958–64) IN THE 61 COUNTY BOROUGHS OF ENGLAND AND WALES WITH A POPULATION OF 80,000 OR OVER IN 1961

Certified cause of death*	Correlation (r)‡ with total water hardness (p.p.m.)			
	45–64 years		65–74 years	
	Male	Female	Male	Female
All causes	−0·55	−0·58	−0·59	−0·58
Cardiovascular disease (17–21): ..	−0·65	−0·63	−0·70	−0·59
Cerebral disease (17)	−0·56	−0·48	−0·56	−0·55
Coronary disease (18)	−0·52	−0·55	−0·47	−0·30
Other heart-disease (20) ..	−0·56	−0·52	−0·47	−0·49
All causes less cardiovascular disease:	−0·35	−0·43	−0·30	−0·43
Bronchitis (24)	−0·45	−0·40	−0·41	−0·42
Cancer, all:	−0·22	−0·09	−0·14	−0·26
Stomach (10)	−0·19	−0·10	−0·16	−0·27
Lung, bronchus (11)	−0·16	+0·02	−0·06	+0·33
Breast (12)	..	+0·12	..	−0·09
Uterus (13)	..	−0·30	..	−0·29
Diabetes (16)†	−0·06	−0·29	..	..
All cardiovascular disease and bronchitis	−0·66	−0·62	−0·70	−0·60
All causes less all cardiovascular disease and bronchitis	−0·26	−0·40	−0·18	−0·40

* Figures in parentheses after cause of death refer to Registrar General's Abridged List.
† Death-rates for all ages.
‡ For normally distributed variables these are the significance levels of the

product moment correlation coefficient (r) for 61 pairs of observations:

$r < -0{\cdot}25$ or $r > +0{\cdot}25$: $P < 0{\cdot}05$.
$r < -0{\cdot}33$ or $r > +0{\cdot}33$: $P < 0{\cdot}01$.
$r < -0{\cdot}41$ or $r > +0{\cdot}41$: $P < 0{\cdot}001$.
$r < -0{\cdot}47$ or $r > +0{\cdot}47$: $P < 0{\cdot}0001$.

In both series, bronchitis is the only sizeable non-cardiovascular cause of death at ages 45-74 showing consistently high correlations with water hardness. In view of the frequent cardiac complications of bronchitis and the considerable interchange of this diagnosis with "myocardial degeneration" on death certificates, this correlation had not been considered previously to contradict the specificity of the association between water hardness and cardiovascular disease. The correlation coefficients of water hardness with mortality from cardiovascular disease and bronchitis together (table I) are much higher than those with all "other" mortality, though these are also negative; these differences are significant in the male but not in the female groups where the correlations with "other" mortality remain high. Of all the individual causes in this "other" group with sufficient numbers to study separately, cancer of the stomach and uterus have consistent negative correlations with water, though of a different order to those of cardiovascular disease.

In the ensuing tables only the results for the 45-64 age-groups are shown; findings in the older groups are very similar. Table II shows the correlations of death-rates with the various chemical components of water hardness. As in the 1951 series, the highest associations of the cardiovascular rates are with temporary hardness (i.e., the carbonate fraction) and calcium; those with sodium much smaller, and with magnesium negligible. Water hardness and calcium are, of course, highly correlated (r=0·95) and the correlations of mortality with water calcium are similar to, though usually higher than, those with total waxer hardness. The calcium content of drinking-water would seem, therefore, to be the relevant component; and since it is a more meaningful entity, and its estimation is more precise than that of total hardness, calcium is used in the further analyses.

TABLE II—ASSOCIATIONS BETWEEN COMPONENTS OF WATER HARDNESS (1961) AND DEATH-RATES AT AGES 45–64 (1958–64) IN THE 61 COUNTY BOROUGHS OF ENGLAND AND WALES WITH A POPULATION OF 80,000 OR OVER IN 1961

Water constituents p.p.m.	Correlation (r)* with death-rates for: Cardiovascular disease		Bronchitis		All "other" causes	
	Male	Female	Male	Female	Male	Female
Total solids	−0·61	−0·58	−0·41	−0·36	−0·23	−0·39
Total hardness: ..	−0·65	−0·63	−0·45	−0·40	−0·26	−0·40
Temporary hardness (carbonate) ..	−0·63	−0·62	−0·48	−0·42	−0·29	−0·36
Permanent hardness (non-carbonate)..	−0·51	−0·45	−0·24	−0·19	−0·10	−0·38
Electrolytes (as ions):						
Calcium	−0·72	−0·71	−0·55	−0·47	−0·37	−0·44
Magnesium ..	−0·02	−0·02	+0·06	+0·01	+0·15	−0·06
Sodium	−0·24	−0·28	−0·25	−0·21	−0·11	−0·19

* Significance levels as in table I.

As previously (Morris, Crawford, and Heady 1961), we have looked for any confounding factor in these associations. Over sixty social and environmental indices, drawn from Census data, were correlated with calcium to investigate the possibility that the correlations between mortality and water calcium (or hardness) are indirect, and reflect only their mutual association with other factors. Table III shows a sample, including and reflecting overcrowding, poverty, climate, and so on, all known to influence mortality; six of the classic factors associated with high mortality in general were combined into a *social factor score* which can be considered to reflect socioeconomic conditions in these towns. All of the correlations with social indices are small, though some are statistically significant. There are relatively high correlations between water calcium and both latitude and period temperature; these two indices are, of course related (r=-0·78) That death-rates are higher in the North is well known, and both climatic and social factors contribute. For cardiovascular disease, however, latitude (or temperature) “effect" seems to be independent of the water “effect” (Morris, Crawford and Heady 1962). Furthermore none of the environmental factors correlated with cardiovascular mortality to the same degree as did water calcium, and, it is safe to say, not one of all the indices included could possibly be producing the high correlations between drinking water and mortality. As in the 1951 series, we have found no indication that water calcium (or hardness) is merely reflecting any other environmental condition that we have been able to identify.

TABLE III—ASSOCIATIONS BETWEEN WATER CALCIUM p.p.m. (1961) AND SOME LOCAL ENVIRONMENTAL INDICES IN THE 61 COUNTY BOROUGHS OF ENGLAND AND WALES WITH A POPULATION OF 80,000 OR OVER IN 1961

Environmental index	Correlation (r) with water calcium
Total population (1961)•	−0·22
Proportion of population aged 65 or over (1961)•	+0·16
Persons per acre (1961)•	+0·16
Proportion of households with 1½ or over persons per room (1961)•	−0·06
Households per car (1961)•†	−0·31
Proportion in lower socioeconomic groups—, i.e. groups 7, 10, 11, 15, 16, 17 (1961)•	−0·13
Proportion in social classes I and II (1951)•	+0·18
Combined social factor score‡	−0·29
Domestic air pollution (1951)§	−0·29
Latitude	−0·37
Long period average temperature (1921–50)¶	+0·42

Significance levels as in table I.

• Registrar General, Census, 1951 or 1961.

† Ministry of Transport (1961).

‡ The social factor score is a weighted linear combination of six indices measuring overcrowding in households, social-class composition, population density, education, all for 1951 (Daly 1959), unemployment for 1927–38 (Morris and Titmuss 1944), and income levels for 1950 (Wilkins 1952). The weights used were those of the first component from a principal component analysis on the six factors.

§ Daly (1959).

¶ Meteorological Office (personal communication).

Multiple Regression Analysis

Correlation analysis is useful in exploring a problem such as this. The correlation coefficient measures how closely variation in one factor is related linearly to variation in another, and neither factor is assumed to be “dependent“ on changes of the other. However, having established a relationship between factors, and postulated which one may be affected by variation of the other, it is of interest to investigate how large this effect may be; the method of linear regression is applicable. Extending this argument and using multiple regression analysis, the relative contributions of several factors to the variation of, for example, a death-rate can be estimated. Table IV shows standardised regression coefficients of death-rates as three variables: water calcium, social factor score (described in table III), and latitude. Broadly, these three variables may be considered to represent water hardness, socioenvironmental, and climatic factors. Together (last column of table IV) they explain a high percentage of the variance between the towns of death-rates for both males and females. The coefficients measure the “effect” on the death-rate of each factor separately when the associations with the other two have been taken into consideration. Water calcium makes a high significant contribution to cardiovascular mortality and a smaller but still significant contribution to bronchitis mortality. Its contribution to “other” male death-rates is not significant, but to “other” female death-rates it makes a significant contribution. The contributions of social factors to the explanation of the variance of cardiovascular mortality is small, but much higher for bronchitis and the rest of the non-cardiovascular mortality. Latitude again seems to have some slight effect (statistically significant at the 5% level) on cardiovascular and bronchitis mortality when water calcium and social factors have been allowed for; this is due, perhaps, to the climatic component. This regression study is focused on cardiovascular mortality, and a broader study of mortality and environment in general will be published elsewhere.

TABLE IV--STANDARDISED REGRESSION COEFFICIENTS OF DEATH-RATES AT AGES 45-64 (1958–64) ON ENVIRONMENTAL FACTORS IN THE 61 COUNTY BOROUGHS OF ENGLAND AND WALES WITH A POPULATION OF 80,000 OR OVER IN 1961

Cardiovascular	Standardised regression coefficient† for:			
Certified cause of death Males: All causes	Water calcium (p.p.m.)	Social factor score	Latitude	% of variance explained
Males: All causes	−0·44***	+0·41***	+0·26*	73%
Cardiovascular disease	−0·61***	+0·03	+0·27	58%
Bronchitis	−0·33**	+0·48***	+0·23	66%
All "other" causes ..	−0·12	+0·64***	+0·16	63%
Females: All causes	−0·48***	+0·38**	+0·15	61%
Cardiovascular disease	−0·54***	+0·27*	+0·23	66%
Bronchitis	−0·26*	+0·43**	+0·23	53%
All "other" causes ..	−0·34*	+0·40**	+0·04	33%

Significance of regression coefficient: * P<0·01, ** P<0·001, *** P<0·0001.

* Coefficients of standardised variables—i.e., reduced to the same mean (zero) and variance (one)—are shown to allow values for the three factors in each cause of death to be compared. The higher of two coefficients is not necessarily the more significant statistically. For

method see Snedecor and Cochran (1967).

Table V illustrates the decline in mortality associated with increasing calcium content of drinking-water in the sixty-one towns. The fall in cardiovascular death-rates is numerically greater and more consistent than that in bronchitis and "other" death-rates, although it is proportionally greater for bronchitis.

TABLE V—MEAN DEATH-RATES AT AGES 45–64 (PER 100,000) BY WATER CALCIUM IN THE 61 COUNTY BOROUGHS OF ENGLAND AND WALES WITH A POPULATION OF 80,000 OR OVER IN 1961

Water calcium (p.p.m.)	No. of towns	All causes		Cardiovascular disease		Bronchitis		All "other" causes	
		Males	Females	Males	Females	Males	Females	Males	Females
<10	8	1688	866	751	355	175	40	762	471
10–19	15	1640	840	751	345	163	34	726	461
20–39	9	1490	765	670	304	129	25	691	436
40–69	9	1528	784	636	306	150	30	742	448
70–99	13	1453	743	633	281	121	25	699	437
100+	7	1260	680	546	248	88	17	626	415

Water Chemistry

Since there is no indication that water is merely reflecting some other factor (though a search for this goes on), the possibility of a direct relationship must be considered and thought given to possible mechanisms. Several suggestions can be made: soft waters could be carrying toxic elements from pipes or soil into supply; hard waters could be protective due to their mineral content; trace elements could be involved. A little progress has been made in investigating these possibilities.

Two separate chemical studies of elements in drinking-water were made by the Atomic Energy Authority and the Government Chemist in representative samples of water from consumers' taps in towns with very soft water and in towns with very hard water. The results were similar. Analyses were made by emission spectroscopy and flame photometry of twenty-one elements, including all likely metal contaminants from water pipes, and trace elements such as cadmium, vanadium, selenium, and molybdenum about which there is evidence of some biological importance even at low concentration.

Possible metal contaminants, copper, zinc, lead, manganese, and iron were all present in concentrations well below the maximum allowable limits set by the World Health Organisation's (1963) International Standards for Drinking Water (Crawford and Morris 1967). Mean concentrations of iron, zinc, lead, tin, nickel, molybdenum, cadmium, chromium, and indium were similar in the two groups of waters. Mean concentrations of copper, selenium, and vanadium in the hard waters were greater than in the soft waters, but this was not consistent in all samples. Table VI shows mean values of those elements which did show consistent differences between the very hard and very soft waters.

TABLE VI—ELEMENTS IN BULKED SAMPLES OF DRINKING-WATER IN TOWNS IN BRITAIN 1962–63

Elements*	9 towns with soft water†		6 towns with hard water‡	
	Mean (µg./l.)	Range (µg./l.)	Mean (µg./l.)	Range (µg./l.)
Calcium	8500	7000–10,000	102,000	90,000–114,000
Magnesium	2500	200–3000	9250	450–14,000

Magnesium ..	[illegible]	[illegible]	[illegible]	[illegible]
Sodium ..	4500	3000–6000	36,000	17,000–55,000
Manganese ..	51	43–58	<10	<10
Aluminium ..	58	30–85	12	<10–19
Boron ..	15	7–22	123	75–170
Iodide ..	1	1	5	3–7
Fluoride ..	40	40	135	90–180
Silica ..	7600	6600–8500	17,300	16,800–17,800

Analyses by Government Chemist of samples taken at a point in the distribution system.

* Only elements showing consistent differences between the soft and hard waters are shown.

† Average total hardness, 29 p.p.m. as calcium carbonate.

‡ Average total hardness, 310 p.p.m. as calcium carbonate.

Discussion

This second study of mortality in the large towns of England and Wales confirms the earlier finding of an association between cardiovascular death-rates and softness of drinking-water, and again, there is no indication that water is merely reflecting some third factor. The correlations are higher than in previous studies and the variation in death-rates over the range of water hardness is substantial; since cardiovascular disease accounts for more than a third of all deaths in middle age in the U.K., a very large number of deaths is involved. A rough estimate of the number of extra deaths in the sixty-one county boroughs associated with differences in water calcium, taking the death-rates of the very hard water areas as baseline, is 2000 per annum for men aged 45-64— i.e., about one-fifth of the deaths—assuming water calcium to be distributed similarly in England and Wales as in these sixty-one county boroughs, this would involve roughly 8000 deaths per annum in men of this age.

The striking similarity of the association between water hardness and mortality in the U.S.A. and U.K. is strong evidence of a “water factor” in cardiovascular disease. Both these countries have the necessary conditions for such a factor to be demonstrated—i.e., large aggregates of population living at different levels of water hardness, a wide range of water hardness, and valid death certification at least for the 45-64 age-group (Heasman and Lipworth 1966). All these conditions have not been present in the studies in Oklahoma and Ireland in which an association was not found (Lindeman and Assenzo 1964, Mulcahy 1964); though in Sweden, with small population aggregates, highly significant associations between cardiovascular mortality and water calcium were in fact found (Biorck et al. 1965); in Holland associations were found in women only (Biersteker 1967). It seems unlikely that the same local factors associated with cardiovascular mortality could be producing indirect correlations with water minerals in several countries. It would seem, therefore, that a “water factor” in cardiovascular mortality exists, although its nature and mode of action still escapes us.

It is important to emphasise that the associations found are with all cardiovascular disease, including cerebrovascular disease, and not with ischemic heart-disease only, although deaths from this cause form the biggest fraction. There are many components of ”cardiovascular disease” —e.g., mural atheroma, intravascular thrombosis, hypertension, and so on. The association could be with any one of these or even with a non-specific element in cardiac failure. Crawford and Crawford (1967) in comparing cardiac lesions found more ischemic myocardial disease in men who had died in a very soft water area than a very hard water area; but there was no increased prevalence of coronary atheroma or stenosis in the soft-water area. Such findings suggested an increased susceptibility of the myocardium in the area with soft water.

In the material described here the association of water hardness and cardiovascular disease is not “specific“—

i.e., death-rates from non-cardiovascular causes are also negatively associated with water hardness, though to a smaller degree. The consistency of the higher association found, however, is remarkable considering the nature of the data and the fact that the components of cardiovascular disease, mentioned above, are not present exclusively in deaths certified to cardiovascular disease (Morris and Crawford 1958). The loss of specificity is greater in the findings for women.

A possibly important finding, not previously mentioned is a highly significant association between infant mortality and water hardness; the correlation (*r*= -0.55 is much higher than that found in the 1951 series. In the past, high infant mortality has been used as a crude index of bad social and health conditions, but with the general rise in the standard of living and great expansion of maternity and other health services, the association between infant mortality and social conditions is considerably less (Martin 1967). It could be that infant mortality is reflecting some factor adverse to health which is correlated with water hardness and which we have not included in the study; or it could be that water minerals are important in infant mortality—a "biological" factor showing up as "social" factors become less important (Morris 1967). Correlations between water hardness and perinatal mortality, postneonatal mortality, and stillbirth are -0·35, -0·44, -0·18, respectively. These associations are being investigated further.

It is not possible to make detailed comparisons between the trace elements studies reported here and those of Schroeder (1966) in the U.S.A., because of differences in sampling. In the U.K., bulked very soft and very hard waters were studied (mean total hardness 29 p.p.m. and 310 p.p.m., respectively); in the U.S.A., Schroeder (1966) compared mean concentrations of constituents in water from twenty-five cities with the lowest and twenty-five cities with the highest death-rates from arteriosclerotic heart-disease in White males 45-64 (mean total hardness 80 p.p.m. and 139 p.p.m., respectively). The main similarities and differences of the two studies, however may be of interest.

In both countries soft waters contained less of each of the three main elements, calcium, magnesium, sodium, as might be expected. Elements showing similar differences between soft and hard waters in both countries are manganese, vanadium, and silicon—manganese being at a higher concentration in soft waters and positively correlated with death-rates from arteriosclerotic heart disease in the U.S.A., and vanadium and silicon being at higher concentrations in hard waters and negatively associated with death-rates in the U.S.A. Copper aluminium are distributed in soft and hard water differently in the U.S.A. and the U.K.: copper being at a higher concentration in hard than soft water in the U.K., the reverse being found in the U.S.A.;.aluminium being at a higher concentration in soft than hard water in the U.K. but not in the U.S.A. In both countries the mean concentrations of iron, lead, molybdenum, and chromium were similar in soft and hard waters.

A high cadmium/zinc ratio in kidneys of rat and mouse has been found to be associated with arterial hypertension (Schroeder et al. 1967) but in the waters analysed for us the cadmium concentration was <0·2 µg. per litre for all soft and hard water examined; there was little difference in zinc concentration between soft and hard waters.

In neither Schroeder's (1966) series nor ours was there any element present in concentrations which could be toxic in conventional terms. However, plumbosolvency may still be a problem in England and waters lying in contact with lead piping for some (Crawford and Morris 1967). Further study of the implications, past and present, of plumbosolvency in the U.K. is now being made. It seems unlikely, however, that lead contamination could be the whole explanation of the "water story" in cardiovascular disease, but it could be an enhancing factor and might explain the much clearer picture and the higher correlations found in the U.K.

The pH of the water could be important, but we have not examined this point because of variations, daily and seasonal, and because of adjustments, by various means, carried out by some water authorities.

The possibility remains that the water minerals themselves may be involved. In England and Wales and Sweden the highest correlations have been with calcium. There was no association with magnesium in England and Wales or in Sweden, but this, of course, does not vitiate the possible importance of magnesium in cardiovascular disease—it merely means that the amount in drinking water is ineffective, as one might expect considering the the quantities in water compared with food. On the other hand, hard drinking-water may provide a meaningful amount of calcium to the diet (Murray and Wilson 1945). Widdowson (1944) showed that about a fifth (200 mg.) of the daily calcium requirement may be obtained by drinking hard water. Widdowson and McCance (1943) estimated that in some localities the calcium in drinking-water could be as important a source of calcium as the foods generally considered to be the main source of this mineral, a fact usually ignored in assessing calcium intakes. Crawford and Crawford (1967) found lower average values for calcium and magnesium in the coronary arteries of young men in a soft-water area compared with those in a hard water area; they suggested that the calcium in drinking water, being in ionised form, could be more readily absorbed and so might make an important special contribution.

Experimental work is increasingly providing evidence for the involvement of calcium and magnesium in electrochemical exchange at cell surfaces associated with changes in adhesion of cells—e.g., endothelium, platelets, and so on (Hughes and Tonks 1965, Curran 1967, Durlach 1967)—and in the myocardium (Bajusz 1965, Nayler 1967), which could be relevant to the present problem.

Our findings do not clarify the problem of the statistical association of mortality and the minerals in drinking water; they do, however, support the suggestion that there is a "water factor” which makes a material contribution, particularly to cardiovascular mortality. It may be that we should be thinking of water as a general factor in mortality operating through the cardiovascular system and therefore more noticeable in cardiovascular (and bronchitis) death-rates. The mechanism may be in the development of heart-failure; incidence and prevalence studies as well as mortality are required to indicate whether the associations of water are with disease or a mode of death. There is urgent need of further studies, individual and ecological (Morris 1967), and the formulation and testing of useful hypotheses for which we must wait on the chemists.

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