CHAPTER FIVE

TRIHALOMETHANE COMPOUNDS FORMATION DURING WATER BLENDING PROCESS

5.1 INTRODUCTION

After the extensive analysis presented in chapter four with respect to the formation and presence of *THM* compounds in distilled water produced by the multi-stage flash distillation (*MSF*) plants in *Kuwait*, the next step is to examine the formation of these compounds during the water blending process. During this process, performed at the water blending complex, brackish water is mixed in certain proportions with distilled water to produce a blended water complying with the requirements of international standards with respect to drinking water quality. During the blending process, chlorination is performed to ensure that the blended water which will be pumped eventually to the consumer is properly disinfected and free from any harmful organisms.

Due to the absence of certain operational parameters, it was not possible to carry out an extensive analysis of *THM* compounds formation, similar to that performed with respect to the distillation plants, within the water blending complex. This chapter will consist of monitoring the formation and, thus, the concentrations of *THM* compounds at key sampling locations. The selection of these locations was designed so as to give an insight into the formation of *THM* compounds. No attempt will be made to construct relevant mass balances over the boundary of the blending plant, due to unavailability of vital data concerning volumetric flow rates of different streams and capacities of storage reservoirs.

In order to match the monitoring programme which was performed on the distillation plants at **Doha East Station**, it was logical to choose **Doha Blending Complex** for the monitoring of *THM* compounds during the blending and chlorination processes. **Doha Blending Complex**, one of four blending complexes existing in *Kuwait*, receives distilled water from both **Doha East** and **Doha West Stations** and is situated about 7 km from both stations.

5.2 WATER BLENDING PRACTICES

The water blending plants form an integral and important link in the drinking water supply system in *Kuwait*. Due to the fact that the distilled water produced by the distillation plants is free from any salts, it is not considered to be adequate for human consumption. Therefore, in order to make this water palatable and to ensure that drinking water conforms to *WHO* guidelines, it is necessary to perform further treatment on this water. This treatments consist of adding suitable amounts of brackish water obtained from underground water resources, *pH* adjustment by adding sodium hydroxide prior to the blending process and finally chlorination before it is pumped to the consumer.

The amount of brackish water which is blended with distilled water depends on many factors such as the salinity of brackish water being utilized, its chemical composition and the requirements of *WHO* guidelines with respect to drinking water. Thus, in practice the blending ratio could vary from 7 to 12 volumes for every 100 volumes of total blended water produced. The *pH* of the distilled water is usually raised from about 6.2-6.5 to around 7.8-8.2 by adding suitable amounts of sodium hydroxide.

At **Doha Blending Complex**, the actual blending process between the distilled water and brackish water occurs at the mixing tank. Distilled and brackish waters are fed into the tank via two separate pipelines. Chlorination is performed by introducing a solution of sodium hypochlorite via a fountain in the middle of the mixing tank. According to design conditions, the level of chlorination dosage is controlled automatically so as to ensure that a minimum residual chlorine of 2.0 mg/L at the tank is always present and that this level does not exceed 2.9 mg/L under any circumstances. This level of chlorination is designed so as to ensure a residual chlorine concentration of 0.5 mg/L at the furthest point in the distribution system. In addition to this the automatic controlling system is supplied complete with an alarm facility, a manual override system is also available. If circumstances such as an emergency or repairs do not allow the introduction of the chlorination solution via the fountain, system design allows the chlorination to be applied to either the brackish water or the distilled water in their respective pipelines prior to entry to the mixing tank.

After the mixing of distilled water with brackish water and chlorination in the mixing tank, the blended water flows for about 100 m to a water storage reservoirs farm. The pipeline which carry the blended water divides into two branches, each of which feed eight underground storage reservoirs. Then the water stored in these storage reservoirs, which are of operational storage nature rather than of strategic nature, flows to the plant pumping station which in turn pumps it either to the distribution network and, thus, the consumer or to the strategic underground reservoirs which are to be found at different locations within the country.

5.3 MONITORING PROGRAMME

The monitoring programme within the blending complex was designed so as to give an insight into the formation of *THM* compounds at key locations within the complex. In order to achieve this aim, five strategic locations were chosen for sampling purposes. The first sampling point was at the end of the pipeline carrying the distilled water being supplied to the blending plant from the distillation plants, while the second sampling point was located at the end of the pipeline carrying the brackish water supplied to the blending plant from the appropriate production centres. The third sampling point location was at the exit of the mixing tank, where blending occurs and contact with chlorination solution is first established. The fourth sampling location was at the end of the pipeline which carry the blended water from the mixing tank to the storage reservoirs, some 100 m away. The fifth and final sampling location was at the pumping station, where the blended and by now chlorinated water is finally pumped beyond the boundaries of the water blending complex. These locations were chosen due to the fact that each represented an important link in the blending complex layout.

The monitoring programme was also structured so as to enable the study of the effect of seasonal variations on the formation of *THM* compounds within the blending plant. For this purpose, three separate monitoring programmes were enacted over three distinct seasonal periods representing summer, winter and spring seasons. The summer monitoring programme covered the period between the 4th of July *1988* and the 15th of August *1988* and coincided with the monitoring of the distillation plants at **Doha East Station**. Eleven sets of data were collected during this period. The winter monitoring programme extended from the 4th to the 15th of December *1988*, during which ten sets of data were collected. Finally, the spring monitoring programme covered the period from the 20th of March to the 18th of April *1989* and included the collection of eight sets of data.

Each set of data covered the measurement of each one of the *THM* compounds at the five locations mentioned above, in addition to determining the level of residual chlorine and recording the temperature and *pH* of each sample.

5.4 *THM* COMPOUNDS FORMATION

Analysis of the data collected from each sampling location covered by the monitoring programme is now presented.

5.4.1 *THM* COMPOUNDS PRESENCE IN BRACKISH WATER

During both the summer and winter seasons monitoring programmes, the chlorination process was applied to the blended water as distilled water is mixed with brackish water. Samples of brackish water collected were, therefore, representative of unchlorinated water. The chemical analysis performed indicated the absence of any *THM* compounds in these samples.

The chemical analysis during the spring season monitoring programme revealed a very different picture. Due to operational problems with the chlorination fountain in the mixing tank, the chlorination process had to be applied to the brackish water before it is mixed with the incoming distilled water in the mixing tank. **Table 20** gives the concentrations of *THM* compounds in brackish water during the spring season. The average value for *THM* compounds is 2.80 ± 1.81 µg/L reaching a maximum value of 5.35 µg/L. **Table 20** and **Figure 16** show that when brackish water is chlorinated, the percentage distribution of the four *THM* compounds is very different to that which results when sea water is chlorinated. Although, bromoform together with bromodichloromethane do still constitute a substantial amount of the total *THM* compounds concentration, the percentage concentration of bromoform is greatly reduced. The reduction of bromoform concentration is primarily due to the much lower concentration of bromide ions of around 1.96 mg/L in brackish water[2] compared to 75.0 ± 0.25 mg/L present in sea water. Brackish water is also characterised by its much lower dissolved organic content (*DOC*) of 0.20 mgC/L compared to 2.30 mgC/L present in sea water[2].

5.4.2 *THM* COMPOUNDS PRESENCE IN DISTILLED WATER RECEIVED BY THE WATER BLENDING PLANT

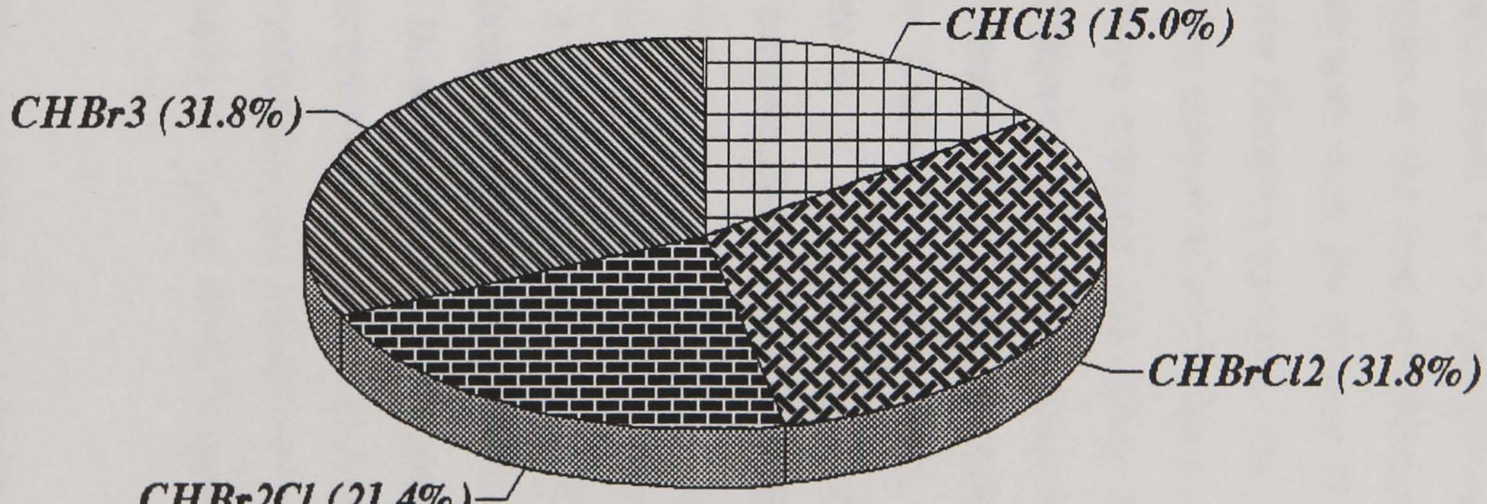
It was very important to determine the concentrations of *THM* compounds in the distilled water being received by **Doha Blending Complex** in order to compare them with the levels of *THM* compounds being detected in the distilled water produced by the two distillation plants which were being monitored at **Doha East Station**; the results of which were extensively discussed in the previous chapter. The main reason for this was, in addition to the fact that it presented a useful opportunity to detect any substantial further formation of *THM* compounds in the distillate during transportation to the water blending complex, that the distilled water being received is a mixture of distillate product, which originates from two adjacent but different water production centres. These are, **Doha East Station** which have seven distillation plants, of which two were being monitored and **Doha West**

TABLE 20
THM COMPOUNDS CONCENTRATIONS IN BRACKISH WATER RECEIVED IN THE BLENDING PLANT IN SPRING

	AVG.	**STD**	**MAX.**	**MIN.**
CONCENTRATION (μg/L)				
$CHCl_3$	0.42	0.50	1.27	0.00
$CHBrCl_2$	0.89	0.55	1.58	0.00
$CHBr_2Cl$	0.60	0.41	1.37	0.00
$CHBr_3$	0.89	0.87	2.43	0.00
TTHM	2.80	1.81	5.35	0.00
RESIDUAL CHLORINE (mg/L)	0.05	0.80	0.25	0.00

FIGURE 16
THM PRESENCE IN BRACKISH WATER

AVERAGE CONCENTRATION = 2.80 ug/L



RESIDUAL CHLORINE = 0.05 mg/L

Station which have sixteen distillation plants, none of which was monitored in this study.

Although, the two above mentioned stations are basically of identical design and are sited next to each other, nevertheless, there are certain differences between them which will undoubtedly have an impact on the level of *THM* compounds in the distillate being produced by each station and, thus, the level of *THM* compounds in the final product received by the water blending complex. The first difference relates to the method of chlorination being utilised at each station. At **Doha East Station** the chlorination process employs chlorine gas, while at **Doha West Station** chlorine is generated by electrolysing sea water solution. The second difference is a rather subtle one which relates to the method of deareation used in the distillation plants of each station. The deareation process in the case of **Doha West Station** distillation plants is of a much more efficient design incorporating stripping steam and pall packing bed leading to enhanced removal of any gases which might be present including of course *THM* compounds. The third difference is related to the respective production of each station. On average and under normal operational practice, it is expected that *two-thirds* of the distilled water being received by **Doha Blending Complex** originate from **Doha West Station** while *one-third* originates from **Doha East Station**. In other words, under normal circumstances, the distilled water being received by **Doha Water Blending Complex** will in most cases be more influenced by the concentrations of *THM* compounds in the distilled water produced by **Doha West Station** as compared to **Doha East Station.**

Table 21 shows the levels of each *THM* compound in the distilled water received by the blending complex during the three monitoring periods. The average value for the total concentrations of *THM* compounds during the summer period was 2.55 ± 1.23 µg/L, ranging from a maximum value of 5.61 µg/L to a minimum value of 1.38 µg/L. The above average value is very near to the value of 3.05 ± 1.35 µg/L that was determined in the previous chapter as an average of the *THM* compounds concentration in distilled water produced by the two monitored distillation units at

Table 21
THM COMPOUNDS CONCENTRATIONS IN DISTILLATE RECEIVED IN DOHA BLENDING PLANT

CONCENTRATION (µg/L)	AVG.	STD	MAX.	MIN.
	SUMMER			
$CHCl_3$	0.00	0.00	0.00	0.00
$CHBrCl_2$	0.14	0.14	0.42	0.00
$CHBr_2Cl$	0.11	0.16	0.53	0.00
$CHBr_3$	2.31	1.19	5.44	1.21
TTHM	2.55	1.23	5.61	1.38
	WINTER			
$CHCl_3$	0.00	0.00	0.00	0.00
$CHBrCl_2$	0.03	0.05	0.15	0.00
$CHBr_2Cl$	0.00	0.00	0.00	0.00
$CHBr_3$	0.94	0.48	1.92	0.37
TTHM	0.97	0.46	1.92	0.37
	SPRING			
$CHCl_3$	0.19	0.25	0.53	0.00
$CHBrCl_2$	1.05	0.46	1.95	0.64
$CHBr_2Cl$	0.48	0.35	0.90	0.00
$CHBr_3$	1.98	1.83	5.92	0.21
TTHM	3.52	2.47	8.15	0.89
	OVERALL			
$CHCl_3$	0.05	0.16	0.53	0.00
$CHBrCl_2$	0.35	0.50	1.95	0.00
$CHBr_2Cl$	0.17	0.29	0.90	0.00
$CHBr_3$	1.75	1.38	5.92	0.21
TTHM	2.33	1.88	8.15	0.37

Doha East Station. The agreement between the two values is considered to be very good, especially when one remembers that the first value is an average over three weeks while the second value is an average over three months, in addition to the fact that the first value covers only two distillation units at **Doha East Station** while the latter value relates in theory to a combination of the seven distillation units at **Doha East Station** and the sixteen units at **Doha West Station**.

The levels of *THM* compounds in the distilled water received by **Doha Water Blending Complex** during the second monitoring period which covers the winter season were rather different. They are characterized by much lower concentrations of *THM* compounds compared to other seasons. An average value of 0.97 ± 0.46 µg/L for *THM* compounds total concentration was determined with a maximum concentration of 1.92 µg/L and a minimum concentration of 0.37 µg/L. A fact which should be kept in mind is that during the winter season many of the distillation plants are taken out of service for annual maintenance. The annual maintenance season usually lasts from *September* to *May* of each year. In certain circumstances, station common systems such as sea water intake structures require maintenance which means that the whole station has to be shut down. It is likely that during the above mentioned winter period, all the distillation plants at **Doha East Station** were out of service. Another very important fact to remember is that in winter, sea water temperature could be at a minimum of around 14°C which means that the rate of formation of *THM* compounds upon chlorination of cooling sea water prior to entry to the distillation plants is much reduced. It has already been shown that the rate of formation of *THM* compounds in chlorinated sea water varies exponentially with temperature. This in turn means that in relative terms more of the *THM* compounds will be removed by the distillation plants due to deareation and venting, resulting in a much reduced concentration of *THM* compounds in the final distillate product.

During the spring monitoring period, an average total concentration of 3.52 ± 2.47 µg/L was recorded for *THM* compounds in the distilled water received by the blending complex, ranging from a maximum of 8.15 µg/L and a minimum of 0.89

µg/L. The most important feature which characterises the data shown in **Table 21** is the relatively high proportion of $CHBrCl_2$ compound, compared to the summer and winter seasons.

Figure 17 illustrates the overall *THM* compounds distribution in the distilled water received by **Doha Water Blending Complex** over the period covered by the three monitoring programmes. The average value for total *THM* concentration was 2.33 ± 1.88 µg/L, which is in very good agreement with the concentration of *TTHM* in distilled water of 3.05 ± 1.35 µg/L which was determined during the monitoring of two distillation plants at **Doha Blending Station**. This agreement becomes more impressive when the suspected influence of **Doha West Station** on *THM* compounds formation in the distilled water received by the blending complex and the impact of seasonal variations are taken into consideration. The figure also indicates the clear dominance of bromoform over other *THM* compounds, though to a slightly reduced extent compared with the dominance that was exhibited in the distilled water produced by the two distillation units being monitored. This lower dominance is believed to be due to seasonal variations in many factors such as the concentration of bromide ions in sea water rather than due to any shifting of distribution between the four *THM* compounds during transportation of distilled water between the distillation plants and the blending complex.

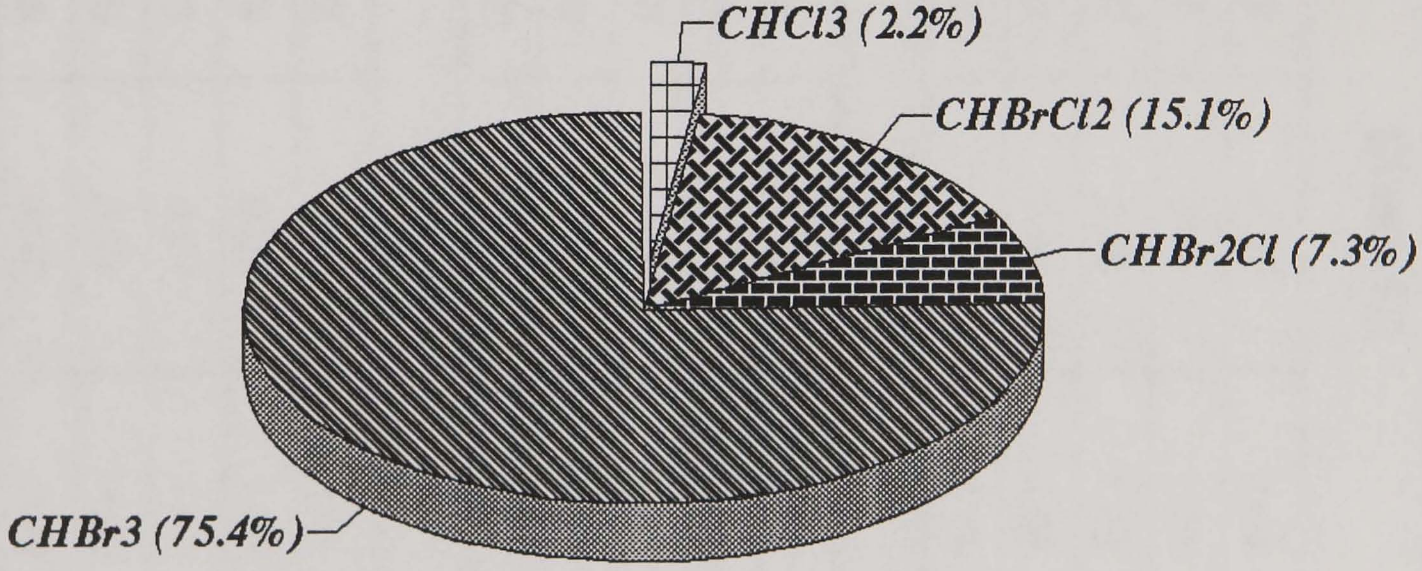
During all three monitoring programmes, residual chlorine was not detected in the distilled water received by the blending plant. This is in agreement with what was found with respect to the absence of residual chlorine in the distilled water produced by the distillation plants.

5.4.3 *THM* COMPOUNDS PRESENCE IN BLENDED WATER AT THE MIXING TANK

Table 22 highlights the concentrations of *THM* compounds at the mixing tank during the three seasonal monitoring periods. The average concentrations for

FIGURE 17
THM PRESENCE IN DISTILLED WATER

AVERAGE CONCENTRATION = 2.33 ug/L



RESIDUAL CHLORINE = 0

Table 22
THM COMPOUNDS CONCENTRATIONS IN MIXING TANK AT DOHA BLENDING PLANT

CONCENTRATION (μg/L)	AVG.	STD	MAX.	MIN.
	SUMMER			
$CHCl_3$	0.15	0.25	0.64	0.00
$CHBrCl_2$	0.46	0.22	0.85	0.00
$CHBr_2Cl$	0.60	0.50	1.80	0.00
$CHBr_3$	2.39	1.01	4.85	1.33
TTHM	3.61	1.43	7.15	1.72
	WINTER			
$CHCl_3$	0.07	0.14	0.37	0.00
$CHBrCl_2$	0.34	0.11	0.53	0.20
$CHBr_2Cl$	0.50	0.15	0.77	0.25
$CHBr_3$	9.28	6.95	24.24	0.54
TTHM	10.20	7.18	25.32	3.00
	SPRING			
$CHCl_3$	0.27	0.56	1.71	0.00
$CHBrCl_2$	0.74	0.25	1.09	0.27
$CHBr_2Cl$	1.06	0.27	1.47	0.74
$CHBr_3$	7.79	3.29	14.93	4.29
TTHM	9.86	3.00	16.90	6.14
	OVERALL			
$CHCl_3$	0.16	0.35	1.71	0.00
$CHBrCl_2$	0.50	0.25	1.09	0.00
$CHBr_2Cl$	0.69	0.42	1.80	0.00
$CHBr_3$	6.26	5.43	24.24	1.33
TTHM	7.60	5.55	25.32	1.72

TTHM compounds were 3.61 ± 1.43 µg/L, 10.20 ± 7.18 µg/L and 9.86 ± 3.00 µg/L for the summer, winter and spring seasons, respectively. The corresponding residual chlorine average concentrations for the summer, winter and spring seasons were 1.68 ± 0.11, 1.81 ± 0.29 and 1.63 ± 0.10 mg/L, respectively. It is clear that the *THM* compounds concentrations are considerably lower during the summer season compared to the winter and spring seasons.

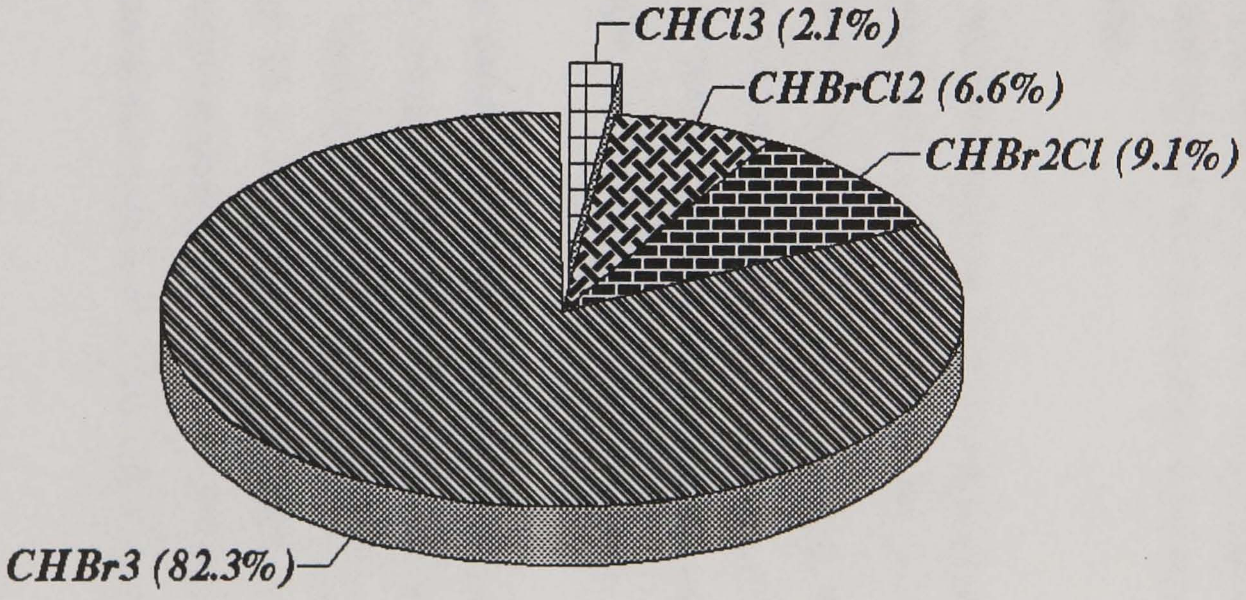
Close examination of the data reveal no substantial differences with respect to the chlorination practice, chlorine dosage level or the concentrations of *THM* compounds and organic precursors in either the distilled water or brackish water received by the blending complex. As a matter of fact, the expectation was that higher concentrations of *THM* compounds would be encountered during the summer season due to enhanced formation potential at higher temperatures. After an exhaustive investigation into the operational parameters and circumstances prevailing during the three monitoring programmes, it was concluded that the unexpectedly low concentrations of *THM* compounds during the summer season was due to venting of these compounds from the mixing tank as the practice was to remove the cover of the tank during the very hot summer days, thus, enabling these volatile compounds to escape into the atmosphere.

Table 22 also lists the overall concentrations of *THM* compounds at the mixing tank. The overall average total concentration for *THM* was 7.60 ± 5.55 µg/L, ranging from a maximum of 25.32 µg/L which occurred in the winter season to a minimum of 1.72 µg/L which occurred in the summer season. The overall average value for the residual chlorine is 1.71 ± 0.21 mg/L.

Figure 18 illustrates the distribution of these compounds. It is clear that bromoform remains the most dominant compound followed by dibromochloromethane and bromodichloromethane.

FIGURE 18
THM PRESENCE IN MIXING TANK WATER

AVERAGE CONCENTRATION = 7.60 ug/L



RESIDUAL CHLORINE = 1.71 mg/L

5.4.4 *THM* COMPOUNDS PRESENCE IN BLENDED WATER BEFORE ENTRY TO THE RESERVOIRS

Measurements of *THM* compounds concentrations at the entrance to the storage reservoirs revealed that there was an increase in these concentrations during all three seasons, with a corresponding decrease in the concentrations of residual chlorine. This is to be expected due to the extra contact time available and the ample presence of residual chlorine.

Table 23 indicates that during the summer season, the average total concentration of *THM* was 5.80 ± 2.59 µg/L, ranging from a maximum of 9.66 µg/L to a minimum of 2.64 µg/L. It also lists the corresponding data for the winter season which shows an average of 10.50 ± 3.90 µg/L, a maximum of 16.96 µg/L and a minimum of 3.74 µg/L and that for the spring season which indicates an average value of 10.18 ± 1.83 µg/L, a maximum of 12.84 µg/L and a minimum of 6.69 µg/L.

Taking an overall view of the three seasonal monitoring programmes the average total concentration for the *THM* compounds at the entrance to the storage reservoirs was 8.63 ± 3.69 µg/L, ranging from a maximum of 16.96 µg/L which occurred during the winter season to a minimum of 2.64 µg/L which occurred during the summer season. The overall average value for the residual chlorine was 1.51 ± 0.13 mg/L, ranging from a maximum value of 1.90 mg/L to a minimum value of 1.30 mg/L.

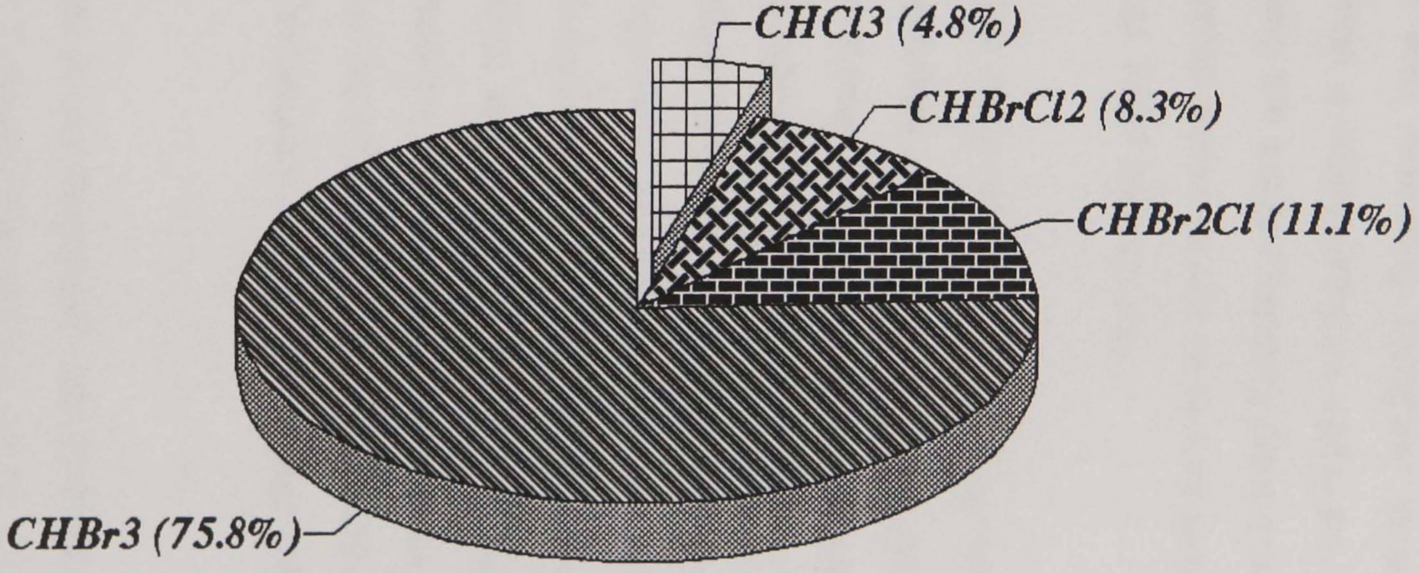
Figure 19 illustrates the distribution of *THM* compounds at the entrance to the reservoirs. It is clear that all four compounds are present now, although bromoform is still the most dominant compound and chloroform the least dominant compound.

Table 23
THM COMPOUNDS CONCENTRATIONS AT RESERVOIRS ENTRANCE AT DOHA BLENDING PLANT

CONCENTRATION (µg/L)	AVG.	STD	MAX.	MIN.
	SUMMER			
$CHCl_3$	0.78	1.16	3.95	0.00
$CHBrCl_2$	0.80	0.72	2.54	0.14
$CHBr_2Cl$	0.92	0.63	2.12	0.36
$CHBr_3$	3.31	1.32	5.89	1.80
TTHM	5.80	2.59	9.66	2.64
	WINTER			
$CHCl_3$	0.09	0.18	0.46	0.00
$CHBrCl_2$	0.43	0.12	0.73	0.31
$CHBr_2Cl$	0.66	0.16	0.97	0.43
$CHBr_3$	9.33	3.87	16.15	2.99
TTHM	10.50	3.90	16.96	3.74
	SPRING			
$CHCl_3$	0.30	0.46	1.37	0.00
$CHBrCl_2$	0.98	0.24	1.55	0.71
$CHBr_2Cl$	1.41	0.58	2.36	0.70
$CHBr_3$	7.48	2.11	10.68	4.50
TTHM	10.18	1.83	12.84	6.69
	OVERALL			
$CHCl_3$	0.41	0.82	3.95	0.00
$CHBrCl_2$	0.72	0.52	2.54	0.14
$CHBr_2Cl$	0.96	0.59	2.36	0.36
$CHBr_3$	6.54	3.74	16.15	1.80
TTHM	8.63	3.69	16.96	2.64

FIGURE 19
THM PRESENCE AT RESERVOIRS ENTRANCE

AVERAGE CONCENTRATION = 8.63 ug/L



RESIDUAL CHLORINE = 1.51 mg/L

5.4.5 *THM* COMPOUNDS PRESENCE IN BLENDED WATER AT THE PUMPING STATION

In many ways, the monitoring of *THM* compounds at the pumping station represents the most important and revealing sampling location. It is at this sampling point that we can obtain a representative value for the level of *THM* compounds concentrations leaving the water blending plant complex. This is due to the fact that by now, the blended water would have had considerable contact time for a substantial formation of *THM* compounds.

Table 24 indicates that during the summer monitoring programme, the average total concentration for *THM* compounds at the blending plant pumping station was 20.32 ± 8.21 µg/L, ranging from a maximum value of 36.33 µg/L to a minimum value of 12.02 µg/L. The average value for residual chlorine was 1.25 ± 0.25 mg/L. It is very clear from the above data that a substantial increase in the concentrations of *THM* compounds have occurred while the blended water have been residing in the storage reservoirs. It should be recalled that when the concentrations of *THM* compounds were last measured at the entrance to the reservoirs, the average total concentration of *THM* compounds was 5.80 ± 2.59 µg/L with a corresponding residual chlorine concentration of 1.49 ± 0.09 mg/L. This increase must be attributed to increased contact time and presence of ample supply of chlorine.

A very similar picture was obtained during the winter monitoring programme. Here, the average total concentration of *THM* compounds was 23.98 ± 4.94 µg/L, ranging from a maximum value of 33.93 µg/L to a minimum value of 17.30 µg/L. The average residual chlorine concentration value was found to be 1.46 ± 0.16 mg/L. It was very interesting to observe during the winter season that the final total concentration of *THM* compounds is very similar to that measured during the summer season, despite the fact that the distilled water received during the winter season was characterised by a much lower *THM* compounds concentrations and the fact, that in common with the spring season, the total concentration of *THM*

Table 24
THM COMPOUNDS CONCENTRATIONS AT PUMPING STATION AT DOHA BLENDING PLANT

CONCENTRATION (μg/L)	AVG.	STD	MAX.	MIN.
	SUMMER			
$CHCl_3$	1.56	1.14	3.80	0.44
$CHBrCl_2$	2.16	0.72	3.83	1.17
$CHBr_2Cl$	6.50	2.83	10.86	2.65
$CHBr_3$	10.10	4.60	17.85	5.13
TTHM	20.32	8.21	36.33	12.02
	WINTER			
$CHCl_3$	0.33	0.35	0.93	0.00
$CHBrCl_2$	2.68	0.41	3.44	1.92
$CHBr_2Cl$	7.85	1.87	11.27	5.42
$CHBr_3$	13.13	2.98	19.63	8.44
TTHM	23.98	4.94	33.93	17.30
	SPRING			
$CHCl_3$	0.62	0.75	2.12	0.00
$CHBrCl_2$	2.15	0.54	3.16	1.30
$CHBr_2Cl$	3.89	0.80	5.61	2.93
$CHBr_3$	9.45	2.60	14.66	5.00
TTHM	16.11	3.43	21.81	10.53
	OVERALL			
$CHCl_3$	0.88	0.99	3.80	0.00
$CHBrCl_2$	2.34	0.63	3.83	1.17
$CHBr_2Cl$	6.25	2.62	11.27	2.65
$CHBr_3$	10.96	3.94	19.63	5.00
TTHM	20.42	6.84	36.33	10.53

compounds at the entrance to the reservoirs were substantially higher compared to the summer season.

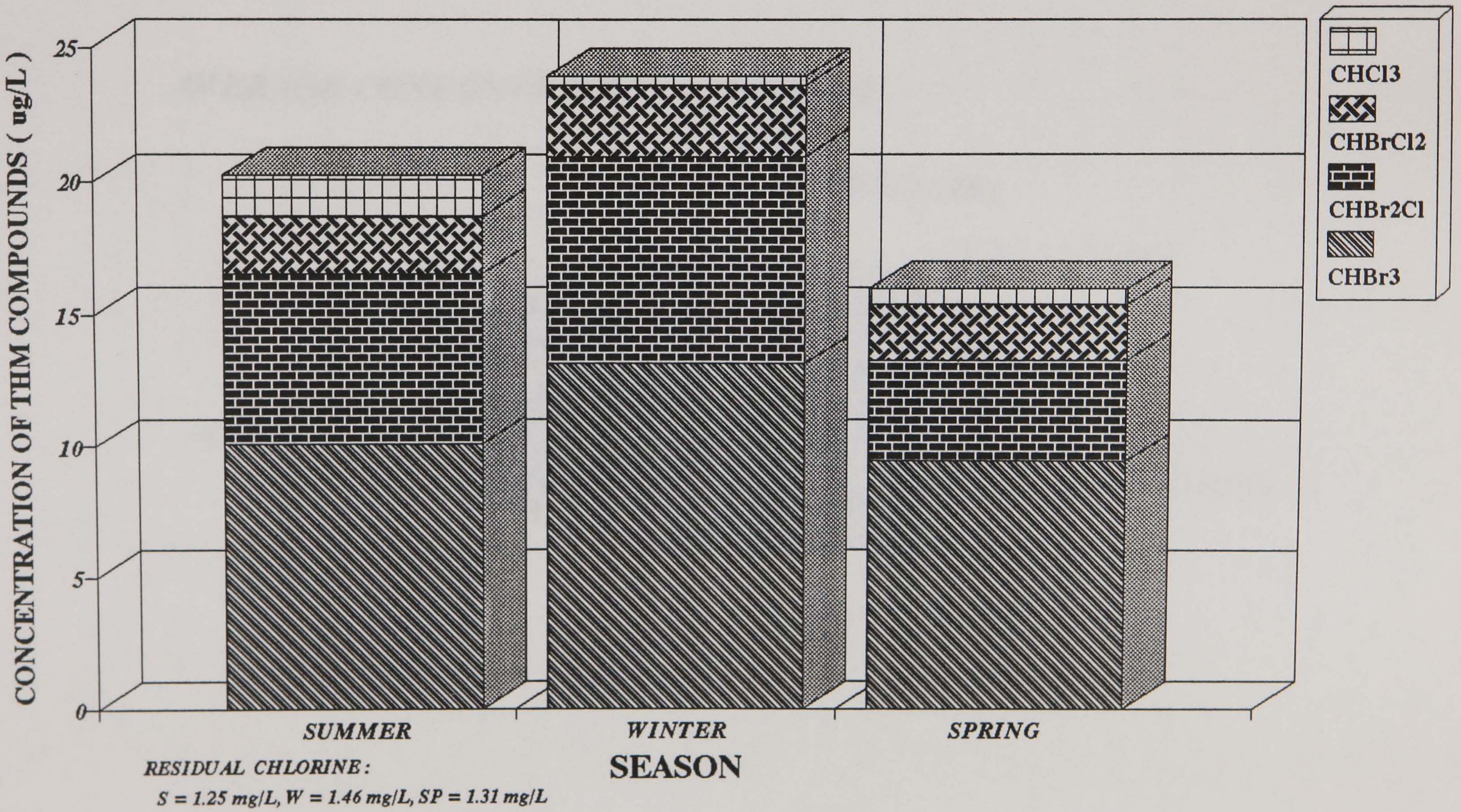
The average total concentration of *THM* compounds at the pumping station during the spring season was estimated to be 16.11 ± 3.43 µg/L, ranging from a maximum value of 21.81 µg/L to a minimum value of 10.53 µg/L. The average value for the residual chlorine concentration during this season was 1.31 ± 0.14 mg/L. It should be recalled that chlorination during this season was applied directly to the brackish water rather than to the blending water in the mixing tank.

It can be determined from data obtained from covering the three seasonal monitoring programmes, that the overall average total concentration of *THM* compounds at the pumping station was 20.42 ± 6.84 µg/L ranging from a maximum of 36.33 µg/L to a minimum of 10.53 µg/L. The overall concentration of residual chlorine at the pumping station was 1.34 ± 0.21 mg/L ranging from a maximum of 1.80 mg/L to a minimum of 0.90 mg/L.

Figure 20 summarizes the concentrations of *THM* compounds at the pumping station during the three seasonal monitoring programmes. The variance displayed with respect to both the total and individual concentrations of *THM* compounds over the seasonal monitoring programmes, is very limited, considering the many different factors which could have an impact on the final concentrations of these compounds such as chlorine dosage, temperature and various operational parameters which might change from day to day.

The distribution of *THM* compounds at the pumping station is rather interesting. So far we have seen a clear dominance of bromoform in all waters which have been sampled and which contain certain concentration of bromide ions. The only exception so far has been brackish water which had a bromide ions concentration of 1.96 mg/L. **Figure 21** clearly shows that the dominance of bromoform is decreasing substantially by the time the blended water is ready to leave the blending complex. Bromoform still constitutes just over 50 % of the total, but

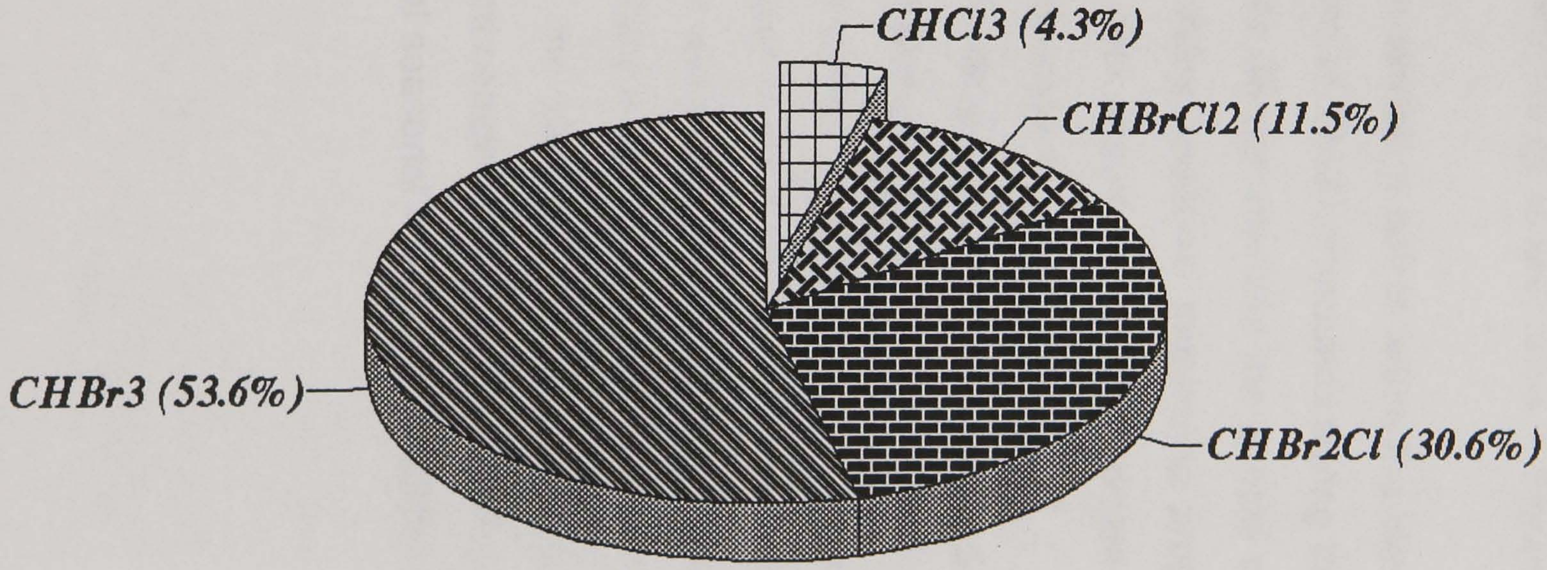
FIGURE 20
THM SEASONAL VARIATION IN BLENDED WATER



RESIDUAL CHLORINE:
S = 1.25 mg/L, W = 1.46 mg/L, SP = 1.31 mg/L

FIGURE 21
THM PRESENCE IN PUMPING STATION WATER

AVERAGE CONCENTRATION = 20.42 ug/L



RESIDUAL CHLORINE = 1.34 mg/L

considerable concentrations of both dibromochloromethane and to a lesser extent bromodichloromethane are now present. In addition, chloroform is also present amounting to just over 4% of the average total *THM* compounds concentration. This overall distribution between the four compounds seem to be valid during the three seasonal monitoring programmes as is illustrated in **Figure 22.**

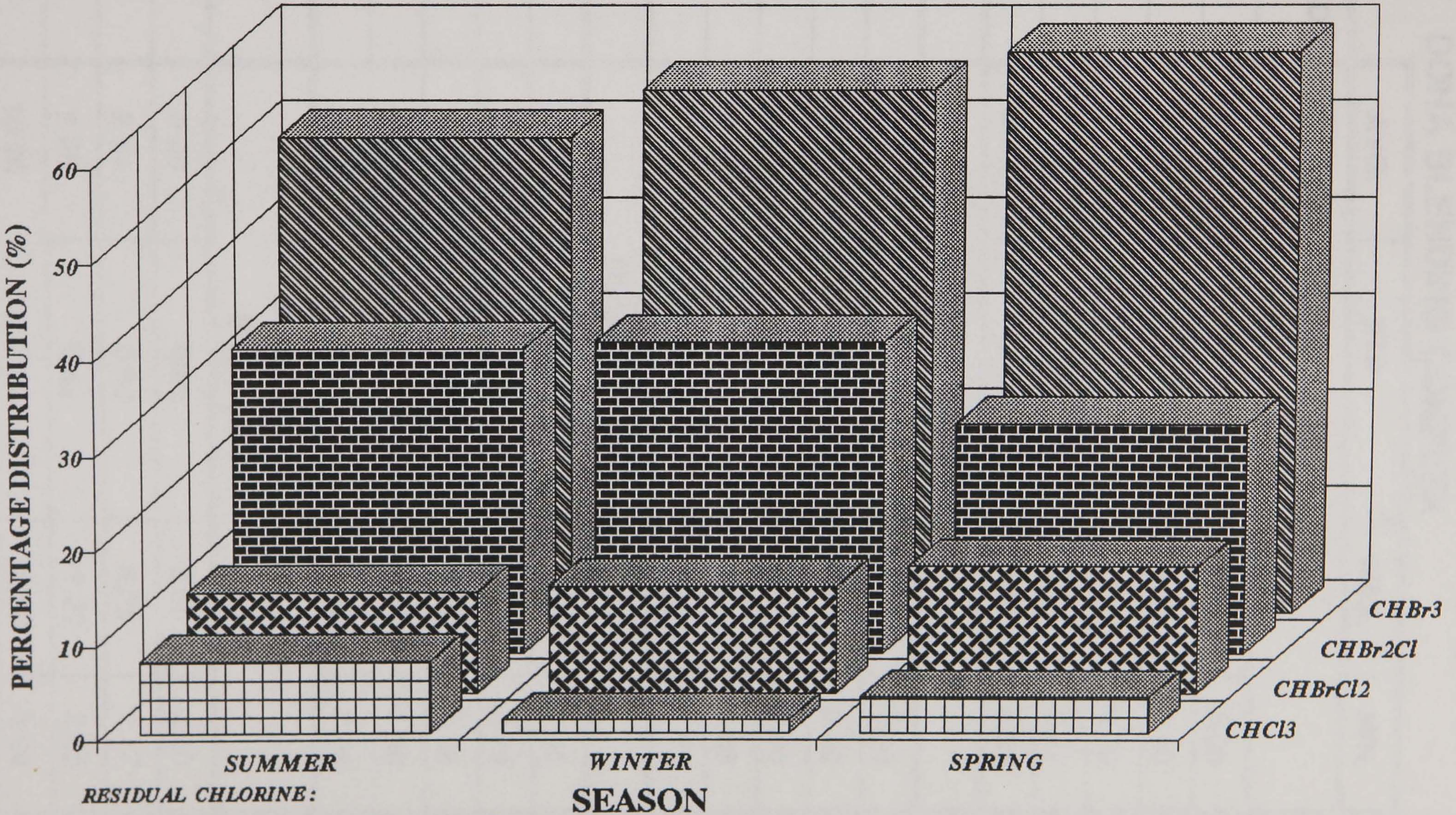
Now that we have covered all the sampling points within the blending complex, it is possible to examine the progress of *THM* compounds during the water blending and chlorination processes. **Table 25** summarizes the overall concentrations of *THM* compounds, covering the three seasonal monitoring programmes, at the different sampling locations. The data shown in the table indicate that the average total concentration of *THM* compounds increases from 2.33 ± 1.88 μg/L in the distillate received by the water blending plant to 20.42 ± 6.84 μg/L in the blended water leaving the boundary of the blending complex. A corresponding decrease in the level of residual chlorine from around 2.00 mg/L to 1.34 ± 0.21 mg/L was also observed. The progressive increase in the concentrations of *THM* compounds at the assigned locations within the water blending complex is clearly illustrated in **Figure 23**. It is clear that two definite step increases occur; one when chlorination is applied and the other while the blended water is residing in the storage reservoirs within the blending plant complex. The above overall picture also apply, to a great extent, to the individual seasonal monitoring programmes, as is clearly illustrated in **Figure 24.**

5.5 CONCLUSIONS

1. The overall average total concentration of *THM* compounds in distilled water received by **Doha Blending Complex** was **2.33** ± **1.88** μg/L ranging from a maximum of **8.15** μg/L in summer to a minimum of **0.37** μg/L in winter. It is very clear that the level of *THM* compounds in distilled water received by the water blending plant is a function of the concentrations of these compounds formed in cooling sea water due to chlorination upon entry to the distillation plants, which in

FIGURE 22

THM SEASONAL VARIATION IN BLENDED WATER



RESIDUAL CHLORINE:

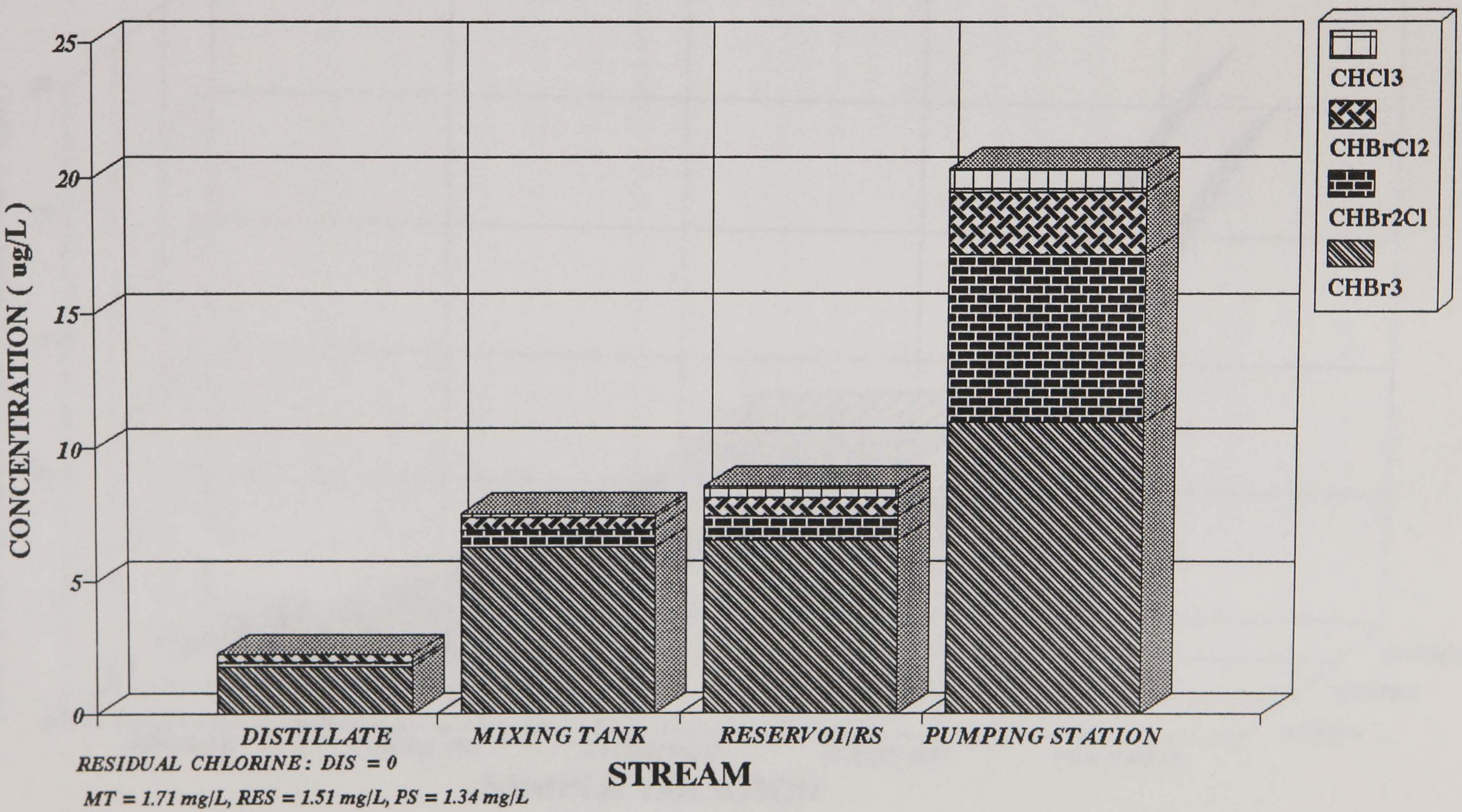
S = 1.25 mg/L, W = 1.46 mg/L, SP = 1.31 mg/L

Table 25
OVERALL *THM* COMPOUNDS CONCENTRATIONS WITHIN DOHA BLENDING COMPLEX

CONCENTRATION (µg/L)	**AVG.**	**STD**	**MAX.**	**MIN.**
	DISTILLATE			
$CHCl_3$	0.05	0.16	0.53	0.00
$CHBrCl_2$	0.35	0.50	1.95	0.00
$CHBr_2Cl$	0.17	0.29	0.90	0.00
$CHBr_3$	1.75	1.38	5.92	0.21
TTHM	2.33	1.88	8.15	0.37
	MIXING TANK			
$CHCl_3$	0.16	0.35	1.71	0.00
$CHBrCl_2$	0.50	0.25	1.09	0.00
$CHBr_2Cl$	0.69	0.42	1.80	0.00
$CHBr_3$	6.26	5.43	24.24	1.33
TTHM	7.60	5.55	25.32	1.72
	RESERVOIRS			
$CHCl_3$	0.41	0.82	3.95	0.00
$CHBrCl_2$	0.72	0.52	2.54	0.14
$CHBr_2Cl$	0.96	0.59	2.36	0.36
$CHBr_3$	6.54	3.74	16.15	1.80
TTHM	8.63	3.69	16.96	2.64
	PUMPING STATION			
$CHCl_3$	0.88	0.99	3.80	0.00
$CHBrCl_2$	2.34	0.63	3.83	1.17
$CHBr_2Cl$	6.25	2.62	11.27	2.65
$CHBr_3$	10.96	3.94	19.63	5.00
TTHM	20.42	6.84	36.33	10.53

FIGURE 23

THM COMPOUNDS FORMATION DURING BLENDING

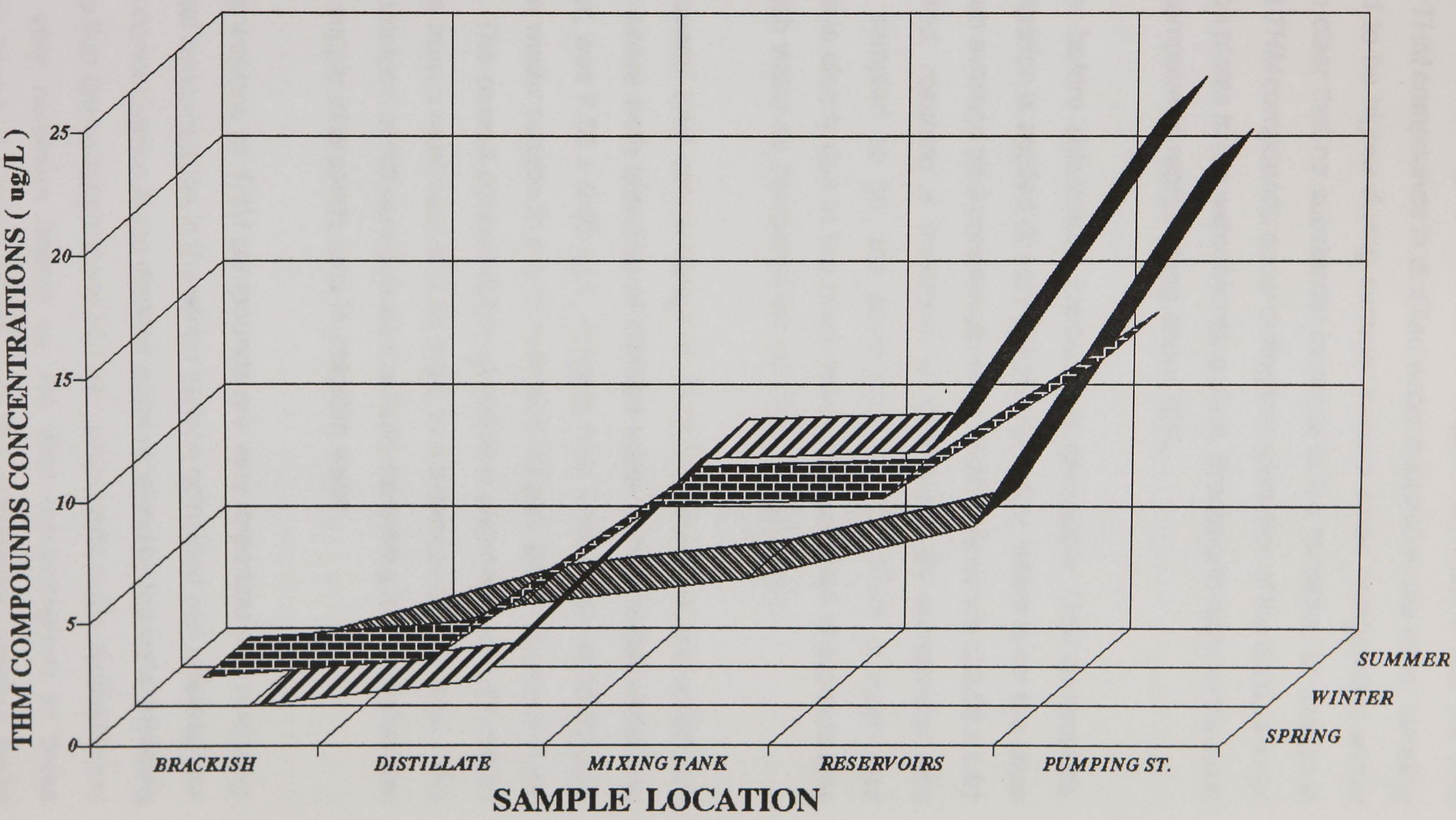


RESIDUAL CHLORINE : DIS = 0

MT = 1.71 mg/L, RES = 1.51 mg/L, PS = 1.34 mg/L

FIGURE 24

THM FORMATION DURING BLENDING PROCESS



turn is dependent on the temperature of sea water. This means that the total concentration of *THM* compounds in distilled water supplied to the water blending plant is expected to be higher during summer season when compared to winter season. It is also clear that no substantial increase in the formation or change in the distribution of *THM* compounds occur during transportation of the distilled water from the distillation plants to the water blending plant. Bromoform remains the most dominant *THM* compounds representing about 75%.

2. Brackish water before chlorination contains no detectable *THM* compounds. However, if chlorination is applied directly to brackish water, which is not the usual normal practice, an average total concentration for *THM* compounds of **2.80** ± **1.81** μg/L was detected, reaching a maximum of **5.35** μg/L. By comparison with different waters sampled so far, the dominance of bromoform is much less pronounced. This is clearly due to the much lower concentration of bromide ions present in brackish water as compared for example to sea water.

3. The average overall total concentration of *THM* compounds at the outlet from the mixing tank, where both blending of distilled water with brackish water and chlorination occur, was **7.60** ± **5.55** μg/L, ranging from a maximum of **25.32** μg/L which occurred in winter season to a minimum of **1.72** μg/L which occurred in the summer season. The overall concentration of residual chlorine was **1.71** ± **0.21** mg/L and ranging from a maximum of **2.50** mg/L to a minimum of **1.50** mg/L. The dominance of bromoform is still very pronounced and if anything is now higher due to the additional supply of bromide ions in brackish water.

The above concentrations of *THM* compounds are very important and revealing. The maximum total concentration in the winter season coincided with relatively low *THM* compounds concentration in the distilled water received by the water blending plant. This means that the concentrations of *THM* compounds in the distilled water received has a very minimum impact on the final concentrations of these compounds in the blended water. Rather, it is the chlorination practice being followed at the water blending plant, in particular the chlorine dosage, which determines these concentrations. With respect to the minimum total concentration which was detected in the summer season, no explanation could be found until it was observed that operators at the blending plant followed the practice of removing the cover of the mixing tank during hot days, especially over the summer months.

4. It is clear that *THM* compounds formation does not cease at the mixing tank. Further formation occurs with increased contact time, provided there is a source of chlorine to sustain the reactions. The overall total concentration of *THM* compounds prior to entry to storage reservoirs at the water blending complex was **8.63** ± **3.69** µg/L, ranging from a maximum of **16.96** µg/L in the winter season to a minimum of **2.64** µg/L in the summer season. This slight increase in the total concentration of *THM* compounds was accompanied by a reduction in the residual chlorine. The overall average concentration of residual chlorine was **1.51** ± **0.13** mg/L, with a maximum of **1.90** mg/L and a minimum of **1.30** mg/L. A similar slight increases in *THM* compounds concentrations were evident, due to the extra contact time between the mixing tank and the entrance to the reservoirs, during the three seasonal monitoring programmes. Furthermore, a slight shift in the distribution of *THM* compounds towards chlorinated species was also evident.

5. Most of the above further formation of *THM* compounds occurred while the blending water was residing in the storage reservoirs. The average overall total concentration of *THM* compounds at the pumping station was **20.42** ± **6.84** µg/L, ranging from a maximum of **36.33** µg/L to a minimum of **10.53** µg/L. This increase in *THM* compounds total concentration was again accompanied by a further reduction in the concentration of residual chlorine. The average concentration of residual chlorine was **1.34** ± **0.21** mg/L, ranging from a maximum of **1.80** mg/L to a minimum of **0.90** mg/L. This further formation of *THM* compounds coupled with a reduction in the concentration of residual chlorine was evident during all three seasonal monitoring programme.

CHAPTER SIX

TRIHALOMETHANE COMPOUNDS PRESENCE IN DRINKING WATER

6.1 INTRODUCTION

So far, it has been possible to cover the progress of *THM* compounds formation beginning with the chlorination of sea water entering the distillation plants situated at **Doha East Station** right up to the blended water leaving the pumping station at **Doha Water Blending Complex**. The final link to cover, is to monitor the fate and possible further formation of these compounds in the water distribution network, during the final journey of the water to the consumer.

In many ways, especially as far as public health is concerned, the level of *THM* compounds in drinking water received by the consumer is the most important aspect of this study. The determined concentrations of these compounds in drinking water should indicate whether or not a problem with respect to public health does exit together with its extent and nature. Knowledge of factors affecting the presence of *THM* compounds in drinking water, coupled with the extensive insight gained so far from analysis of the formation of these compounds during both sea water distillation and water blending processes, would be of paramount importance in controlling and minimizing their presence in drinking water.

For the purpose of this study, it was not practical for the monitoring programme to cover the whole country. At the same time, it was of vital importance that it is possible to be able to relate the presence of *THM* compounds in drinking water with that already covered in the distilled water produced by **Doha East Station** and blended water pumped by **Doha Blending Complex**. Therefore, certain districts had to be covered which receive drinking water from the above water blending complex and water production station. They had to be selected so that they also provide an insight into the effect of contact time. In order to be able to evaluate the concentrations of *THM* compounds properly, some other districts which are served by another water blending complex had to be covered.

Most of the monitoring programme, concerned with the level of *THM* compounds in drinking water was, performed during the spring season. A limited monitoring programme was also performed during the summer season in order to determine the effect of higher water temperature on the formation of these compounds.

6.2 DRINKING WATER SUPPLY SYSTEM

The drinking water supply system in *Kuwait* is an integrated system which starts with the blended water leaving the different Blending Water Complexes and ends with the consumer's tap. Altogether, there are four different water blending complexes. These include: **Shuwaikh Blending Plant** which serves the centre of *Kuwait* city; **Shuaiba Blending Plant** which serves part of the southern region of the country, but mainly the oil refining centres; **Doha Blending Plant** which serves most of *Kuwait* city and surrounding suburbs; and finally **Al-Zour Blending Plant** which serves most of the population and industrial centres in the southern region of the country.

The water which leaves any of the above mentioned blending complexes, after undergoing blending and chlorination, is pumped using main pumping stations, either directly to the consumer via the water distribution network or to the strategic storage reservoirs which are situated at different locations within the country. These storage reservoirs are mostly underground concrete structures of very large capacities, ranging up to 254567 m^3 (56 MIG). The total storage capacity of these reservoirs amounted 7.85 Million m^3 (1727 MIG) in *1988*. In addition, a further storage capacity of 118196 m^3 (26 MIG) exits in the form of elevated towers which are used for operational purposes, such as maintaining suitable pressure in the network during peak-time consumption.

The water stored in the underground reservoirs constitutes a strategic reserve which is used during emergencies. Usually, this water remains stored for extended periods of time. Therefore, it becomes very important to ensure that the quality of water being stored in these reservoirs is maintained up to *WHO* standards for drinking water. To ensure this, the quality of water residing in these reservoirs is continually monitored for any adverse changes. Each storage reservoirs complex is capable of circulating the water within the complex, where further chlorination could be applied if necessary. This rechlorination practice ensures that the water remains disinfectant and suitable for human consumption, regardless of storage time, but of course does introduce a further supply of chlorine which tends to enhance further *THM* compounds formation.

In *1988*, the water distribution network in *Kuwait* extended for 4515 km and covered most of the country residential, commercial and industrial centres. It consists of main transportation pipelines which link the different water blending complexes and water storage reservoirs, main distribution pipelines which distribute water to secondary pumping stations and finally secondary distribution pipelines which distribute water to individual consumers. The water distribution network utilizes different piping and fitting materials, depending on location within the network, such as cement lined ductile iron, galvanized steel and copper pipes.

The objective of the distribution network is to provide the consumer with clean drinking water satisfying the requirements of *WHO* drinking water standards. To ensure that the water remains disinfectant, chlorination practice at the blending plants and further rechlorination at the storage reservoirs must ensure that a residual chlorine of 0.05 mg/L exist at the furthest point in the network.

6.3 MONITORING LOCATIONS

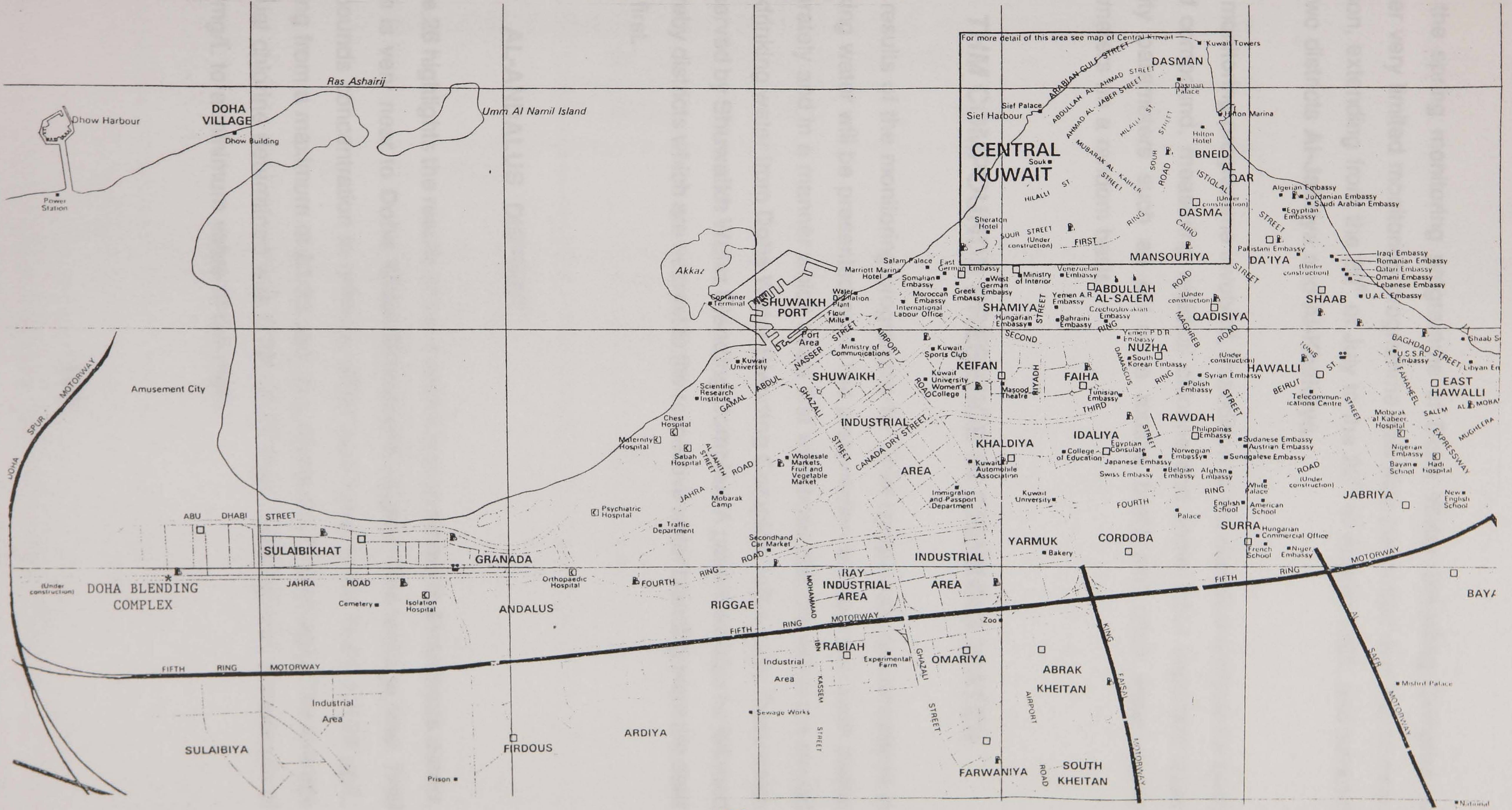
The monitoring programme of *THM* compounds in drinking water was limited to *Kuwait* city boundary. This was in part dictated by the fact that the intention was to try and map out the fate of these compounds in the blended water produced by **Doha Blending Complex**, the concentrations of which had already been monitored. This meant that the monitoring programme must cover districts within the city which are essentially supplied by blended water produced by **Doha Blending Complex**. Furthermore, some other districts not supplied with drinking water from **Doha Blending Complex** had to be covered in order to have a suitable basis for comparison. A map of *Kuwait* city is shown in **Figure 25** which illustrates the location of the districts covered in the monitoring programmes in addition to showing the location of **Doha Water Blending Complex** and **Doha East Power Generation & Water Production Station**.

The districts served by **Doha Water Blending Complex** which were covered in the monitoring programme include **Al-Andalus, Al-Jabriya** and **Hawalli** districts. **Al-Andalus** district, which is a new but growing residential area, was selected because it is situated near to the blending plant, while both **Al-Jabriya** and **Hawalli** districts were selected because they are two of the furthest districts served by **Doha Blending Complex**. Both of these districts are mainly residential areas, however, **Al-Jabriya** is a rather new and well-off district while **Hawalli** is an old and highly populated district with some commercial centres and, thus, characterized by high drinking water consumption.

In addition to the above three districts, it was decided to monitor two more districts within *Kuwait* city. These two districts were **Keifan** and **Al-Sharq**, both served by **Shuwaikh Water Blending Complex**. This blending plant, together with **Doha Water Blending Complex**, serve the whole of *Kuwait* city and its northern suburbs. The above two districts are situated very near to **Shuwaikh Water Blending Complex**, which because it was the first to be built in the country is now situated very near to the city centre. Shuwaikh Water Blending Plant is supplied with distilled water by the distillation plants situated at **Shuwaikh Station**. Both the station and the blending plant utilizes chlorine gas for the chlorination of cooling sea water entering the distillation plants at the station and for the chlorination of blended water at the blending plant. **Keifan** district is a residential area, very similar in many respects to **Al-Jabriya** district, while **Al-Sharq** is partly residential but mainly commercial.

Simultaneous monitoring of all districts was performed during the spring of *1989* extending over the period from the 21st of March to the 22nd of April. This coincided

FIGURE 25
A MAP OF KUWAIT CITY



with the spring monitoring programme of **Doha Water Blending Complex**. A further very limited monitoring programme was also performed over the summer season, extending from the 20th of July to the 22nd of August 1988, and covered the two districts **Al-Jabriya** and **Al-Khaldiya**.

The monitoring programme involved, in addition to the chemical analysis for each *THM* compound, measuring residual chlorine and some other important water quality parameters such as *pH* on a routine basis and other water quality parameters on a random basis.

6.4 *THM* COMPOUNDS PRESENCE IN DRINKING WATER

The results of the monitoring programme for *THM* compounds concentrations in drinking water will be presented now. The presentation will deal with each district separately and in a manner which deals first with those districts which are served with drinking water from **Doha Water Blending Complex**, followed by those which are served by **Shuwaikh Water Blending Complex**. A pattern will also be followed whereby districts which are nearest to the respective water blending plant are dealt with first.

6.4.1 AL-ANDALUS DISTRICT

Table 26 highlights the results of the monitoring programme in **Al-Andalus** district, which is very near to **Doha Water Blending Complex**. The average total *THM* compounds concentration in drinking water was found to be 16.65 ± 3.29 µg/L, ranging from a maximum of 23.38 µg/L to a minimum of 12.40 µg/L. The average residual chlorine determined was 0.79 ± 0.08 mg/L, ranging from a maximum of 0.90 mg/L to a minimum value of 0.6 mg/L.

TABLE 26

THM COMPOUNDS CONCENTRATIONS IN DRINKING WATER IN AL-ANDALUS DISTRICT

	AVG.	STD	MAX.	MIN.
CONCENTRATION (μg/L)				
$CHCl_3$	0.52	0.68	1.96	0.00
$CHBrCl_2$	1.95	0.43	2.76	0.99
$CHBr_2Cl$	4.61	1.05	7.18	2.74
$CHBr_3$	9.56	2.77	16.78	5.76
TTHM	16.65	3.29	23.38	12.40
RESIDUAL CHLORINE (mg/L)	0.79	0.08	0.90	0.60

The above concentrations of *THM* compounds are very similar to those obtained at the pumping station of **Doha Water Blending Complex** during the same period, which amounted to 16.11 ± 3.43 µg/L. However, although the concentrations of *THM* compounds have not changed, there was a definite further consumption of the residual chlorine which was found to be 1.31 ± 0.14 mg/L at the pumping station. The conclusion is, therefore, either there was further formation of *THM* compounds which subsequently escaped to the atmosphere or that the depletion of chlorine should be attributed to other reasons.

Figure 26 illustrates the relative distribution of *THM* compounds in drinking water sampled at this district. The distribution shown, which indicates that bromoform constituted 57.5%, dibromochloromethane 27.7%, bromodichloromethane 11.7% and chloroform 3.1%, matches excellently with the *THM* compounds distribution obtained at the pumping station of **Doha Water Blending Complex** during the same period of time. This indicates that in addition to no further *THM* compounds formation occurring, no significant shifting in the relative distribution of the four compounds did occur.

6.4.2 AL-JABRIYA DISTRICT

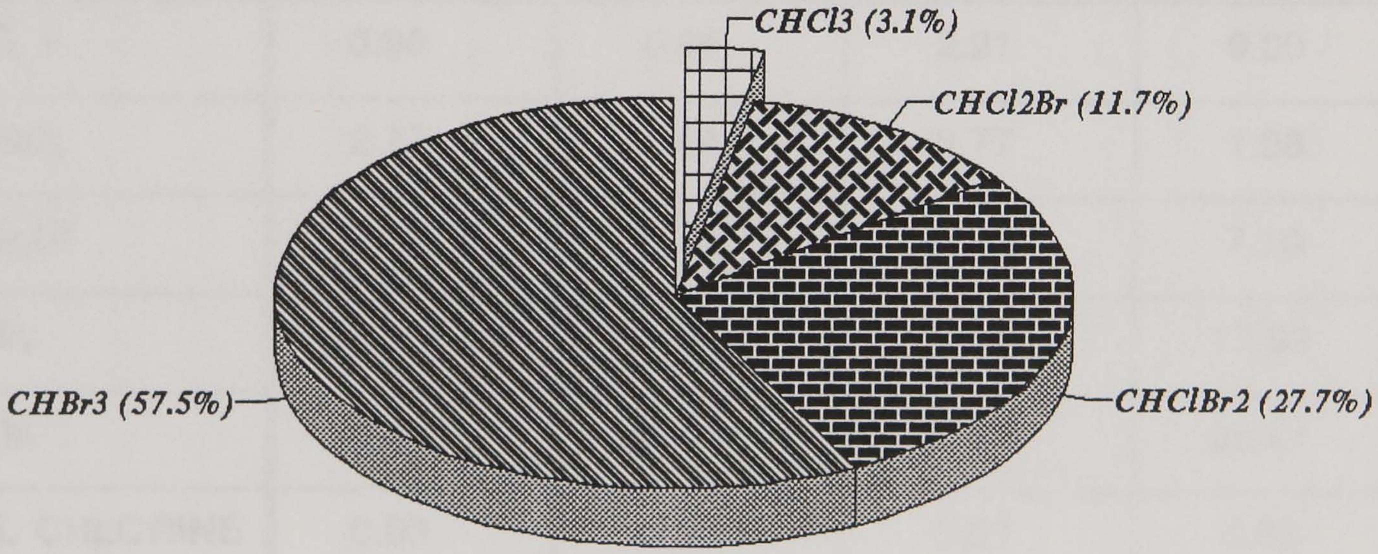
The **Al-Jabriya** district which is supplied with water from **Doha Water Blending Complex** is much further away from it compared to **Al-Andalus** district. **Table 27** indicates that the average total concentration of *THM* compounds in drinking water sampled in **Al-Jabriya** district was 37.51 ± 5.99 µg/L, ranging from a maximum of 53.98 µg/L to a minimum of 28.44 µg/L. The detected average residual chlorine in this district was 0.63 ± 0.08 mg/L, ranging from a maximum of 0.80 mg/L and a minimum of 0.50 mg/L.

The above concentrations of *THM* compounds indicate that compared to those detected at **Al-Andalus** district, a slightly higher than two-fold increase has occurred with some accompanied consumption in chlorine, expressed in a reduction

FIGURE 26

THM DISTRIBUTION IN AL-ANDALUS DISTRICT

AVERAGE CONCENTRATION = 16.65 ug/L



RESIDUAL CHLORINE = 0.79 mg/L

TABLE 27
THM COMPOUNDS CONCENTRATIONS IN DRINKING WATER IN AL-JABRIYA DISTRICT

	AVG.	STD	MAX.	MIN.
CONCENTRATION (μg/L)				
$CHCl_3$	0.90	0.98	2.91	0.00
$CHBrCl_2$	2.77	0.51	3.77	1.98
$CHBr_2Cl$	9.19	1.50	13.73	7.10
$CHBr_3$	24.65	4.98	36.79	17.62
TTHM	37.51	5.99	53.98	28.44
RESIDUAL CHLORINE (mg/L)	0.63	0.08	0.80	0.50

in the detected residual chlorine from an average value of 0.79 ± 0.08 mg/L to an average value of 0.63 ± 0.08 mg/L. It is clear that the increased contact time with the availability of residual chlorine has lead to further formation of *THM* compounds.

In addition to the above further formation in *THM* compounds, it seems that a change in the relative distribution of these compounds has also occurred. **Figure 27** indicates a definite shift towards brominated compounds. The contribution of each compound is as follows: bromoform 65.7%, dibromochloromethane 24.5%, bromodichloromethane 7.4% and chloroform 2.4%. Altogether, the brominated compounds constitute between them 97.6% of the total *THM* compounds concentration.

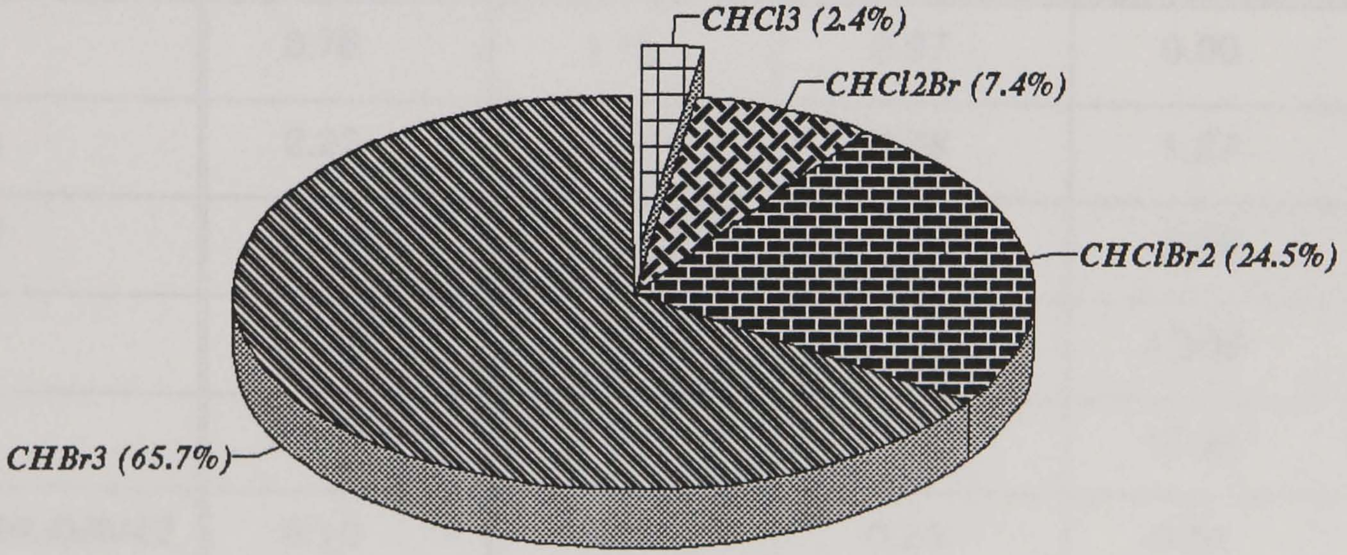
6.4.3 HAWALLI DISTRICT

Hawalli district is situated very near to **Al-Jabriya** district. As shown in **Table 28**, the average total concentration of *THM* compounds was found to be 34.31 ± 7.09 µg/L, ranging from a maximum of 44.82 µg/L to a minimum of 17.86 µg/L. The average detected residual chlorine was found to be 0.10 ± 0.06 mg/L, ranging from a maximum value of 0.20 mg/L and a minimum value of 0.01 mg/L.

The concentrations of *THM* compounds detected in **Hawalli** district is very similar to those found existing in **Al-Jabriya** district. This is not surprising considering that both districts are very near to each other. However, the residual chlorine at **Hawalli** district has dropped to an average value of 0.10 ± 0.06 mg/L, compared to an average value of 0.63 ± 0.08 mg/L at **Al-Jabriya** district. The absence of any further matching *THM* compounds formation could be due to the unavailability of any organic precursors necessary to sustain any *THM* compounds formation, or the fact that chlorine consumption was due to other reasons such as much higher water consumption in **Hawalli** district.

FIGURE 27
THM DISTRIBUTION IN AL-JABRIYA DISTRICT

AVERAGE CONCENTRATION = 37.51 ug/L



RESIDUAL CHLORINE = 0.63 mg/L

TABLE 28
THM COMPOUNDS CONCENTRATIONS IN DRINKING WATER IN HAWALLI DISTRICT

	AVG.	STD	MAX.	MIN.
CONCENTRATION (µg/L)				
$CHCl_3$	0.76	1.15	3.97	0.00
$CHBrCl_2$	2.22	0.57	3.78	1.27
$CHBr_2Cl$	7.04	1.62	9.11	3.16
$CHBr_3$	24.30	4.99	33.29	12.89
TTHM	34.31	7.09	44.82	17.86
RESIDUAL CHLORINE (mg/L)	0.10	0.06	0.20	0.01

Figure 28, which illustrates the relative contribution of each *THM* compound at **Hawalli** district, indicates that the shift towards brominated compounds have continued. The contribution of *THM* compounds are as follows: bromoform 70.8%, dibromochloromethane 20.5%, bromodichloromethane 6.5% and finally chloroform 2.2%. It is clear now that with continuing depletion of residual chlorine and increased contact time that brominated compounds are favoured.

6.4.4 KEIFAN DISTRICT

The data relevant to **Keifan** district, which is served by **Shuwaikh Water Blending Complex**, is shown in **Table 29**. The average total concentration of *THM* compounds was found to be 56.81 ± 22.25 µg/L, ranging from a maximum of 82.77 µg/L to a minimum of 8.39 µg/L. The average residual chlorine concentration detected was 0.06 ± 0.06 mg/L, ranging from a maximum of 0.15 mg/L and a minimum of zero.

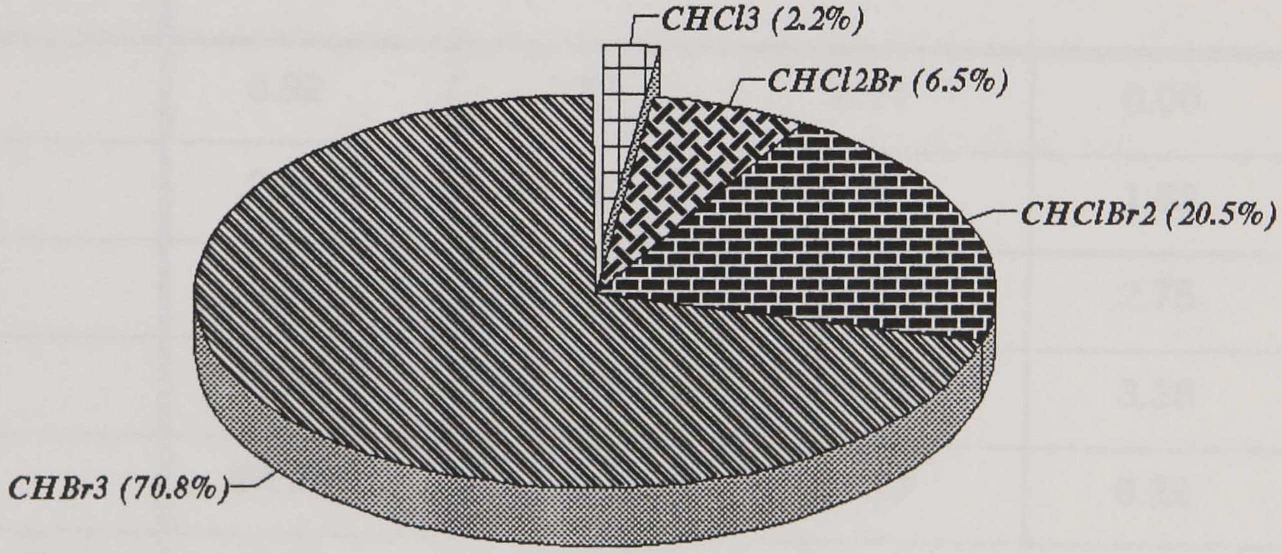
The relative contribution of each *THM* compound at **Keifan** district is illustrated in **Figure 29**. The dominance of brominated compounds, especially bromoform, is clearly evident. The contribution of each compound is as follow: bromoform 83.5%, dibromochloromethane 9.9%, bromodichloromethane 5.0% and chloroform 1.6%.

6.4.5 AL-SHARQ DISTRICT

The concentrations of *THM* compounds at **Al-Sharq** district were very similar to those obtained at **Keifan** district as shown in **Table 30**. The average total concentration of *THM* compounds was found to be 54.59 ± 22.50 µg/L, ranging from a maximum of 92.35 µg/L to a minimum of 12.31 µg/L. The average residual chlorine concentration was found to be 0.10 ± 0.09 mg/L, with a maximum of 0.30 mg/L and a minimum of zero.

FIGURE 28
THM DISTRIBUTION IN HAWALLI DISTRICT

AVERAGE CONCENTRATION = 34.31 ug/L



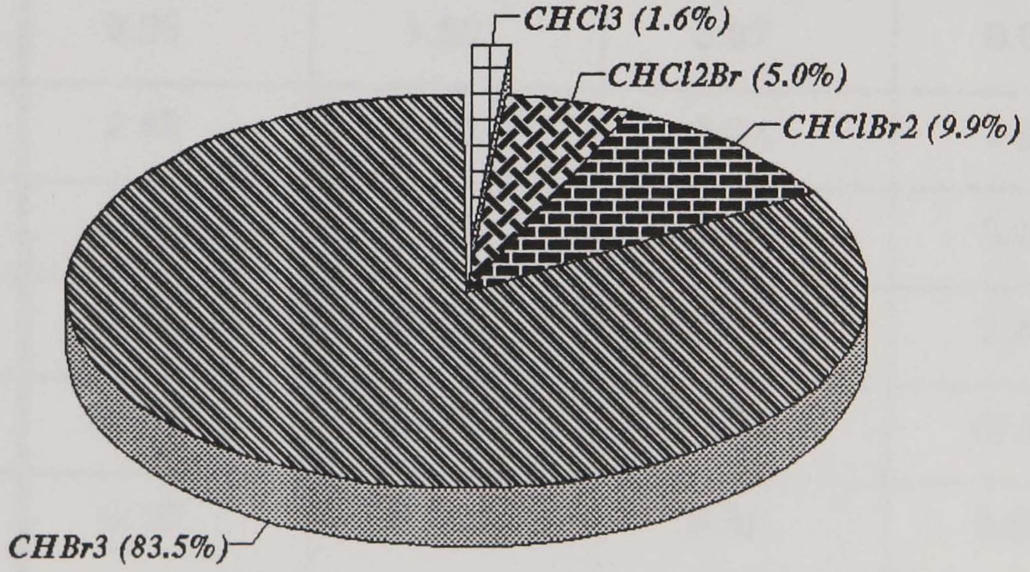
RESIDUAL CHLORINE = 0.10 mg/L

TABLE 29
THM COMPOUNDS CONCENTRATIONS IN DRINKING WATER IN KEIFAN DISTRICT

	AVG.	STD	MAX.	MIN.
CONCENTRATION (μg/L)				
$CHCl_3$	0.92	1.07	3.11	0.00
$CHBrCl_2$	2.86	1.40	7.87	1.62
$CHBr_2Cl$	5.60	1.41	9.11	2.75
$CHBr_3$	47.43	20.87	71.52	3.38
TTHM	56.81	22.25	82.77	8.39
RESIDUAL CHLORINE (mg/L)	0.06	0.06	0.15	0.00

FIGURE 29
THM DISTRIBUTION IN KIEFAN DISTRICT

AVERAGE CONCENTRATION = 56.81 ug/L



RESIDUAL CHLORINE = 0.06 mg/L

TABLE 30

THM COMPOUNDS CONCENTRATIONS IN DRINKING WATER IN AL-SHARQ DISTRICT

	AVG.	STD	MAX.	MIN.
CONCENTRATION (μg/L)				
$CHCl_3$	0.96	1.52	5.87	0.00
$CHBrCl_2$	2.40	0.49	3.34	1.61
$CHBr_2Cl$	6.72	1.54	10.25	3.02
$CHBr_3$	44.51	20.34	77.42	7.41
TTHM	54.59	22.50	92.35	12.31
RESIDUAL CHLORINE (mg/L)	0.10	0.09	0.30	0.00

The contribution of each *THM* compound at **Al-Sharq** district is illustrated in **Figure 30**. The distribution shown is very similar to that witnessed at **Keifan** district. The dominance of brominated compounds, especially bromoform, is still clearly evident. The contribution of each compound is as follow: bromoform 81.5%, dibromochloromethane 12.3%, bromodichloromethane 4.4% and chloroform 1.8%.

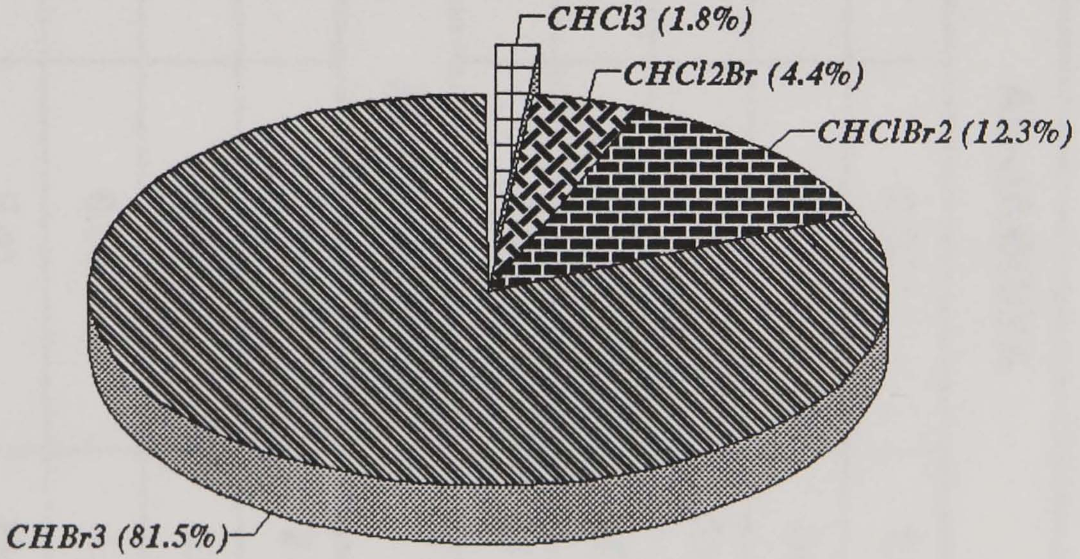
6.5 IMPACT OF SEASONAL VARIATIONS

The impact of temperature on the concentrations of *THM* compounds in drinking water was determined by performing a limited monitoring programme during the summer season. The principle difference between the spring and summer seasons is the temperature of the blended water leaving the water blending plant. The average water temperature during the spring season was 28°C, while the average temperature during the summer season was 39°C. Other parameters such as *pH*, residual chlorine and chemical composition of the water were all found to be comparable during both seasons. Two districts in *Kuwait* city were monitored, which included **Al-Khaldiya** and **Al-Jabriya**. The first of these districts is served with drinking water from **Shuwaikh Water Blending Complex** while the latter is served by **Doha Water Blending Complex**.

Table 31 indicates that the average total *THM* compounds concentration during the summer season at **Al-Jabriya** district was found to be 75.94 ± 4.30 μg/L, ranging from a maximum of 81.25 μg/L to a minimum of 67.72 μg/L. This compares with an average value of 37.51 ± 5.99 μg/L during the spring season. The corresponding average residual chlorine during the summer season monitoring programme was 0.64 ± 0.12 mg/L, with a maximum of 0.80 mg/L and a minimum of 0.50 mg/L. As the levels of residual chlorine at **Al-Jabriya** district during both seasons were very similar, the increased concentrations of *THM* compounds must be due to enhanced formation as a result of higher water temperatures during the summer season. **Figure 31** illustrates the relative contribution of each *THM* compound during the summer season. No significant changes compared to the

FIGURE 30
THM DISTRIBUTION IN AL-SHARQ DISTRICT

AVERAGE CONCENTRATION = 54.51 ug/L



RESIDUAL CHLORINE = 0.10 mg/L

TABLE 31
THM COMPOUNDS CONCENTRATIONS IN DRINKING WATER DURING SUMMER SEASON

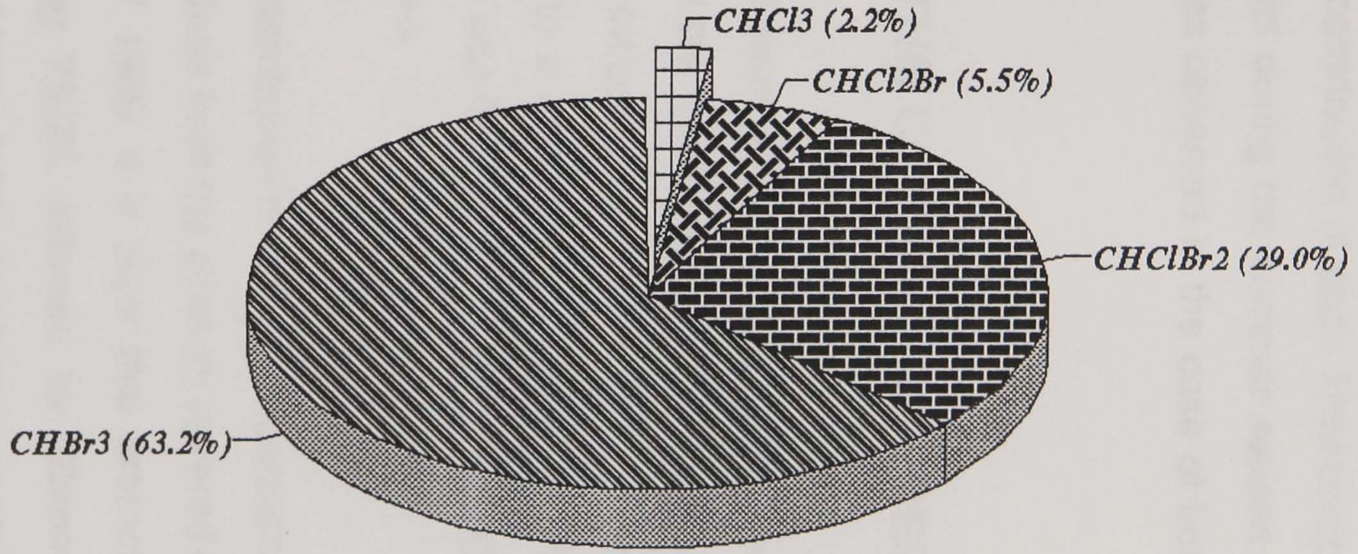
CONCENTRATION (μg/L)	AVG.	STD	MAX.	MIN.
AL-JABRIYA				
$CHCl_3$	1.70	0.27	2.14	1.27
$CHBrCl_2$	4.18	0.56	5.21	3.52
$CHBr_2Cl$	22.04	1.19	23.30	19.69
$CHBr_3$	48.02	2.95	52.03	43.07
TTHM	75.94	4.30	81.25	67.72
AL-KHALDIYA				
$CHCl_3$	1.43	0.51	2.15	1.01
$CHBrCl_2$	2.18	0.60	3.02	1.69
$CHBr_2Cl$	4.22	0.33	4.57	3.78
$CHBr_3$	73.98	2.41	75.96	70.59
TTHM	81.82	2.99	85.14	77.89

FIGURE 31

THM DISTRIBUTION IN AL-JABRIYA DISTRICT

SUMMER SEASON

AVERAGE CONCENTRATION = 75.94 ug/L



RESIDUAL CHLORINE = 0.62 mg/L

relative distribution obtained during the spring season were apparent. In order to confirm the above level of *THM* compounds concentrations during the summer season, samples from another district were analysed. **Table 31** indicates that average total concentration of *THM* compounds at **Al-Khaldiya** district was 81.82 ± 2.99 µg/L, ranging from a maximum of 85.14 µg/L to a minimum of 77.89 µg/L. **Figure 32** illustrates the relative contribution of each *THM* compound for samples collected from **Al-Khaldiya** district during the summer season. This contribution seems to be in line with what was observed in the case of both **Keifan** and **Al-Sharq** districts.

6.6 OVERALL VIEW OF *THM* COMPOUNDS PRESENCE

By examining the data obtained from all districts, it was possible to reach an overall view. This examination of the data, shown in **Table 32**, revealed that the average total concentration of *THM* compounds was 40.04 ± 20.97 µg/L, ranging from a maximum of 92.35 µg/L to a minimum of 8.39 µg/L. The corresponding concentration of residual chlorine was 0.34 ± 0.32 mg/L, ranging from a maximum of 0.90 mg/L to a minimum of zero.

Figure 33 illustrates the overall distribution of *THM* compounds in drinking water in *Kuwait* based on the data obtained from the districts covered by the monitoring programme during the spring of *1989*. It is clear that bromoform is the most dominant compound, constituting 75.3% followed by dibromochloromethane, constituting 16.6%, followed by bromodichloromethane, constituting 6.1%, and finally chloroform which constituted only 2.0%. Thus, brominated trihalomethanes accounted for nearly 98% of the total *THM* compounds detected in drinking water in *Kuwait*.

The variance in the average concentrations of *THM* compounds at different districts is clearly displayed in **Figure 34**. It is clear that two districts, including, **Al-Jabriya** and **Hawalli**, which are served by **Doha Water Blending Complex** have similar

FIGURE 32

THM DISTRIBUTION IN KHALDIYA DISTRICT

SUMMER SEASON

AVERAGE CONCENTRATION = 81.82 ug/L

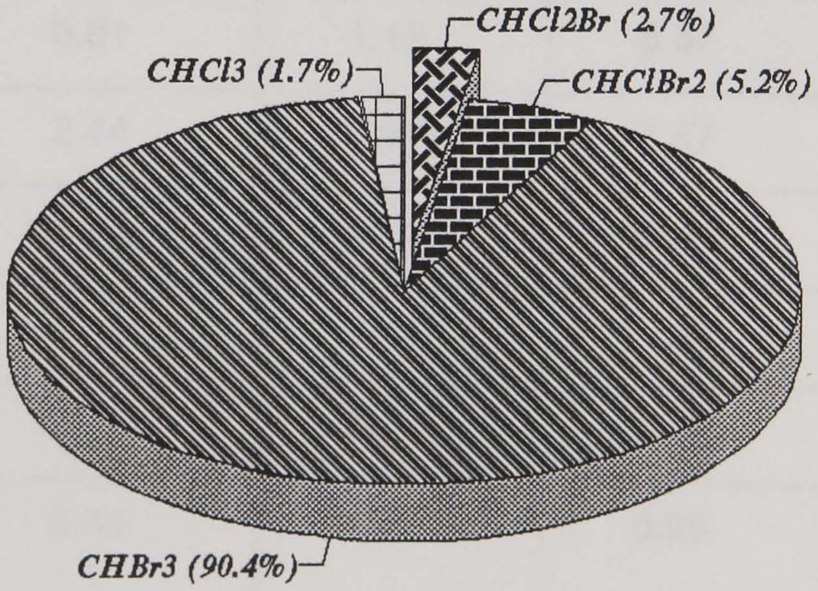


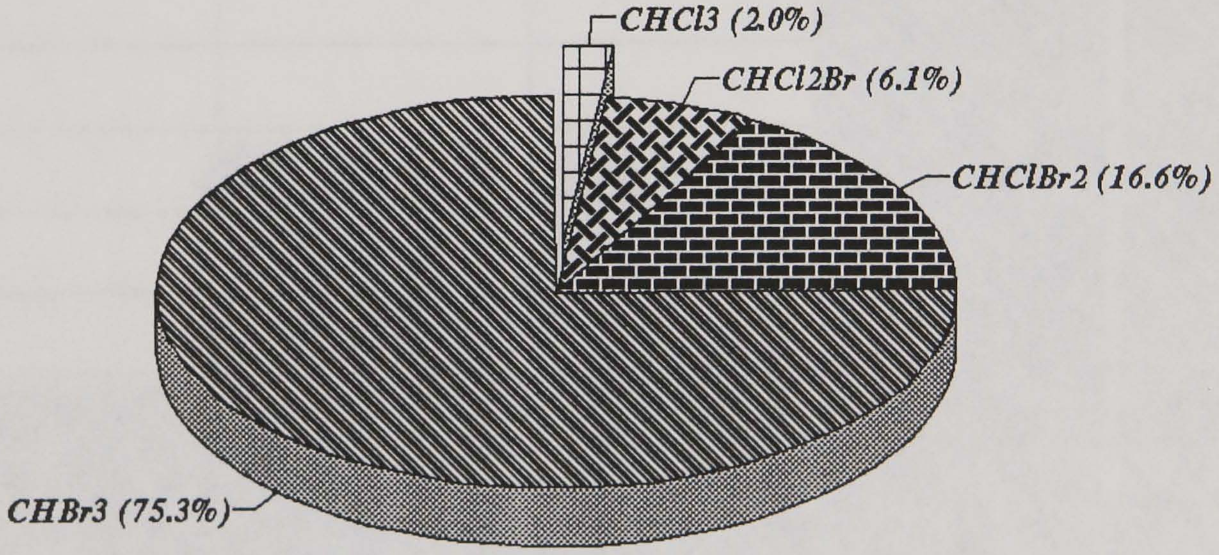
TABLE 32
OVERALL *THM* COMPOUNDS CONCENTRATIONS IN DRINKING WATER IN KUWAIT CITY (SPRING *1989*)

	AVG.	STD	MAX.	MIN.
CONCENTRATION (μg/L)				
$CHCl_3$	0.81	1.13	5.87	0.00
$CHBrCl_2$	2.44	0.84	7.87	0.99
$CHBr_2Cl$	6.63	2.11	13.73	2.74
$CHBr_3$	30.16	19.60	77.42	3.38
TTHM	40.04	20.97	92.35	8.39
RESIDUAL CHLORINE (mg/L)	0.34	0.32	0.90	0.00

FIGURE 33
THM DISTRIBUTION IN DRINKING WATER

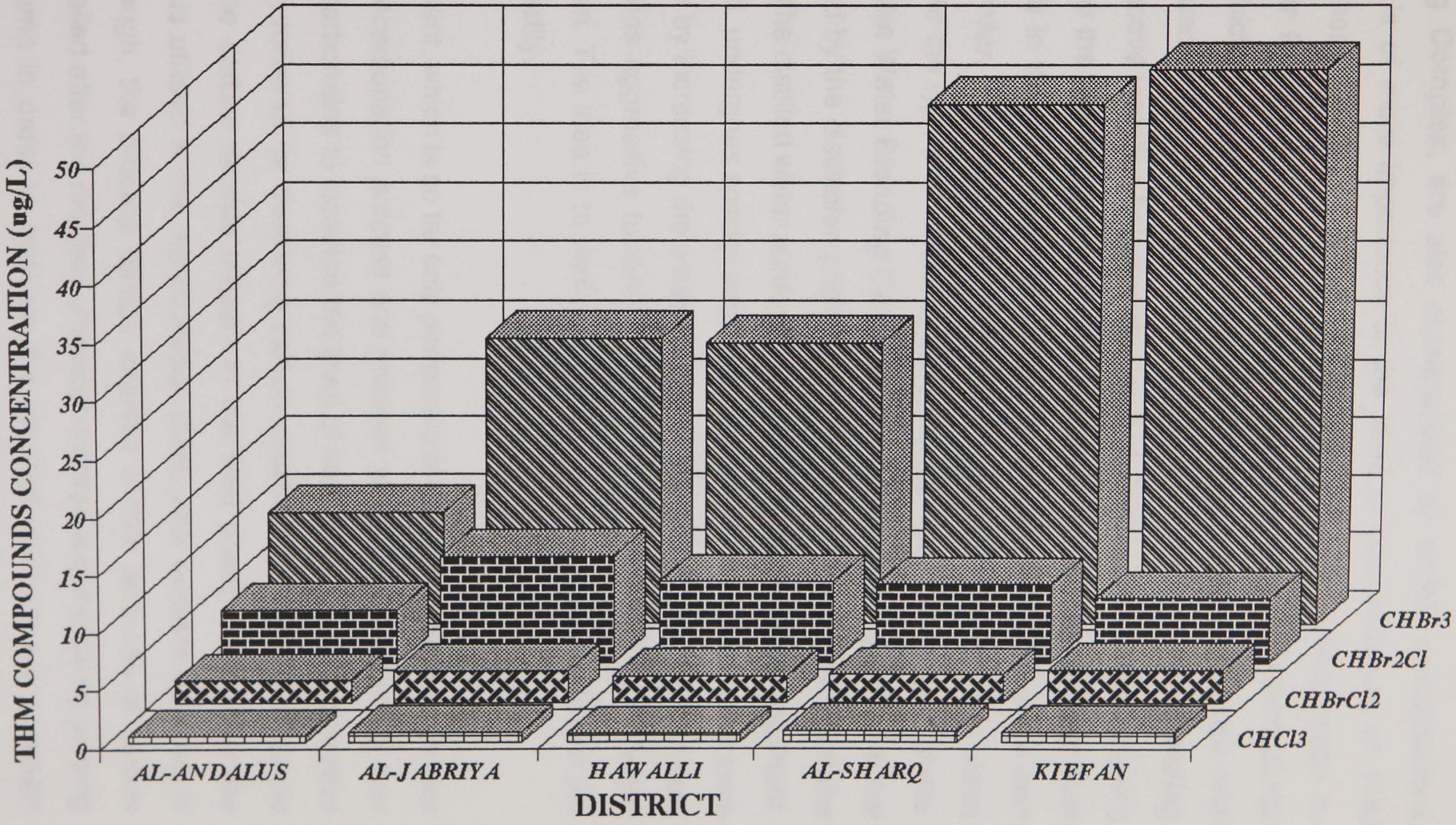
SPRING 1989

AVERAGE CONCENTRATION = 40.04 ug/L



RESIDUAL CHLORINE = 0.34 mg/L

FIGURE 34
THM CONCENTRATION IN DRINKING WATER



concentrations, while the remaining two districts, which are served by **Shuwaikh Water Blending Complex**, are also characterized by similar concentrations. However, what is of more importance is the level of concentrations of *THM* compounds at these districts. The two districts served with drinking water by **Shuwaikh Water Blending Complex** have an average total *THM* compounds concentration which is higher by about 50% compared to the average total concentration found at the other two districts served by **Doha Water Blending Complex**. The above variation between the level of *THM* compounds in drinking water obtained by the two blending plants is of particular significance. Apart from minor differences in the chlorination practices, the chlorination process at both plants is very similar. However, a vital difference exists between the two plants which is related to the type and nature of distilled water received by both plants. In the case of **Doha Water Blending Complex**, the distilled water received is that which is produced by the distillation plants situated at both **Doha East** and **Doha West Stations**. The distilled water received by **Shuwaikh Water Blending Plant**, on the other hand, undergoes special treatment designed to make the water more chemically stable by increasing the alkalinity of the final drinking water produced, thus, making it less aggressive towards the different components of the water distribution system. The idea is to minimize corrosion damage and maintain the drinking water quality.

The above treatment, which is so far only performed at **Shuwaikh Station**, is best described as a *recarbonation process* and involves passing distilled water over beds of calcium carbonates to increase the level of both calcium and carbonates ions in the water, followed by dissolving carbon dioxide in it. Due to economic considerations, the carbon dioxide present in the vent gases expelled by the distillation plants is utilised in the recarbonation plant, after suitable polishing is carried out. Although, the process design requires certain amounts of carbon dioxide to be expelled after the required chemical reaction is complete by utilising an aeration column in order to maintain the required optimum *pH*, a certain amount of carbon dioxide must dissolve and remain in the now stabilised distilled water. As it was clearly shown that the vent gases expelled by the distillation plants are highly enriched with *THM* compounds, it is absolutely certain that some intake of these compounds by the distilled water does occur during the recarbonation process, despite the aereation process which is part of the process design.

With respect to the relative distribution of *THM* compounds in drinking water at the different districts, **Figure 35** illustrates that a trend similar to that observed in **Figure 34** is still evident. The most important observation which is clearly displayed is that the percentage contribution of bromoform to the total *THM* compounds concentration increases with increasing total concentration. The dominance of bromoform is clear at all districts but is especially pronounced at districts served with drinking water which originates from **Shuwaikh Water Blending Plant**. It is strongly suspected that the increased bromoform content at these districts is due to bromoform intake by the distilled water during the recarbonation process. It should be remembered that bromoform was found by far to be the most abundant *THM* compound in the vent gases expelled by the distillation plants.

It seems that the strongest correlation occurs between the concentration of *THM* compounds and residual chlorine. It is very evident that with increased contact time there is a depletion in residual chlorine resulting in further formation of *THM* compounds. This correlation is evidently displayed in **Figure 36**.

6.7 CONCLUSIONS

Based on the monitoring programme concerned with the concentrations of *THM* compounds in drinking water in a number of districts in *Kuwait*, the following conclusions could be made :-

1. The overall average total concentration of *THM* compounds in drinking water, based on the monitoring programme covering five different districts in *Kuwait* city during the spring season, was found to be **40.04** ± **20.97** μg/L. The maximum concentration encountered was **92.35** μg/L, while the minimum concentration

FIGURE 35
THM DISTRIBUTION IN DRINKING WATER

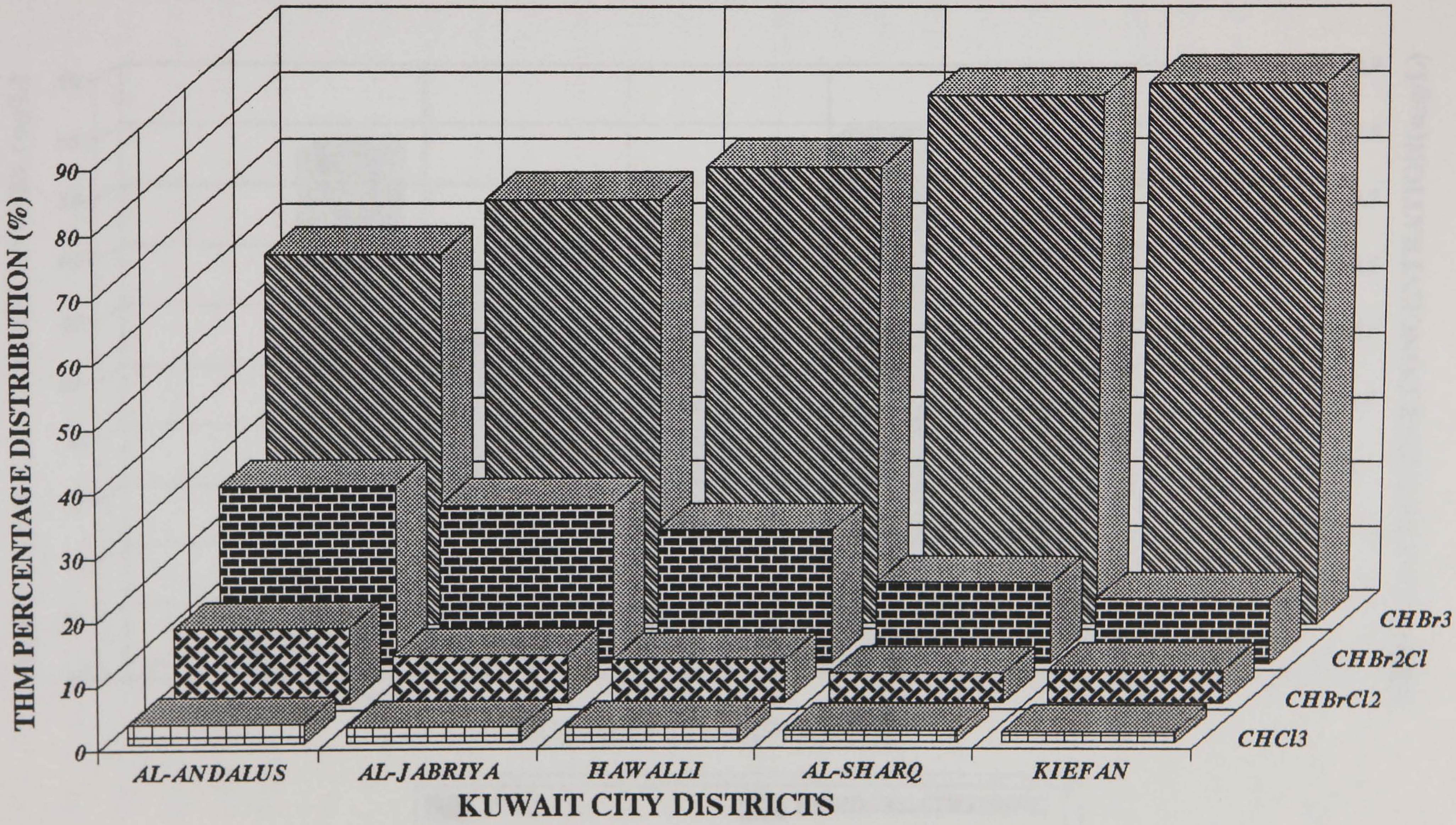
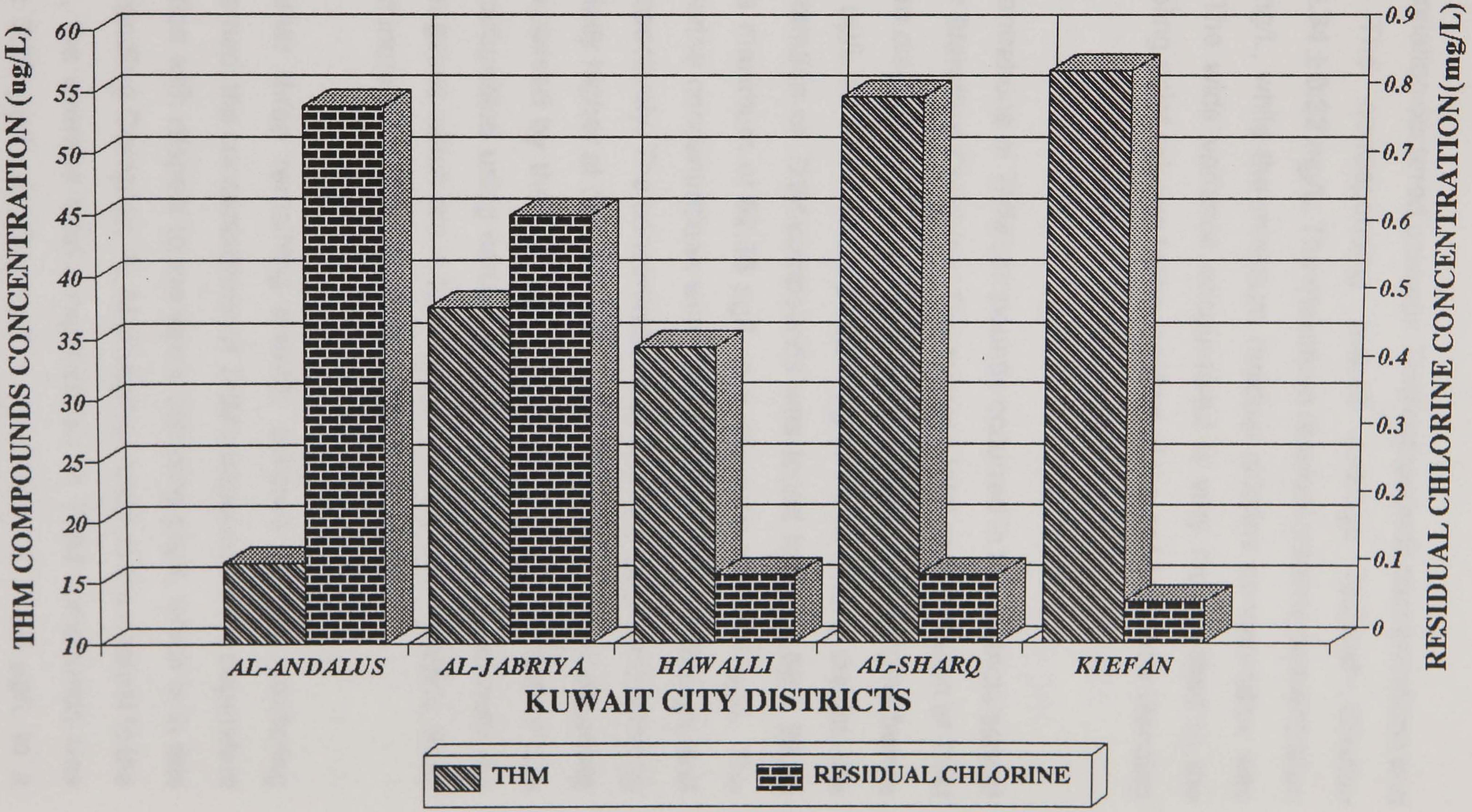


FIGURE 36
THM & RESIDUAL CHLORINE CONCENTRATIONS



detected was **8.39** µg/L.

2. The strongest correlation occurred between *THM* compounds concentrations and residual chlorine. The corresponding overall average residual chlorine concentration was **0.34** ± **0.32** mg/L. The maximum residual chlorine concentration detected was **0.9** mg/L, while the minimum residual chlorine concentration was found to be zero. The wide variance encountered is very much linked to the location of the sampling point relative to the location of the serving water blending plant.

3. The highest concentrations of *THM* compounds occurred in two districts served by **Shuwaikh Water Blending Complex**. The average total concentration of *THM* compounds at **Keifan** district was found to be **56.81** ± **22.25** µg/L, ranging from a maximum of **82.77** µg/L to a minimum of **8.39** µg/L. At **Al-Sharq** district, the average total concentration of *THM* compounds was found to be **54.59** ± **22.50** µg/L, ranging from a maximum of **92.35** µg/L to a minimum of **12.31** µg/L. The average residual chlorine concentrations were found to be **0.06** ± **0.06** mg/L and **0.10** ± **0.09** mg/L, respectively. The concentrations of *THM* compounds in drinking water were substantially higher at districts served by **Shuwaikh Water Blending Complex**. This is explained by the fact that the distilled water received by this blending plant is recarbonated using carbon dioxide which is retrieved from the distillation plants vent gases which are in turn very rich in *THM* compounds, thus, leading to substantial increase in the intake of these compounds.

4. As far as the other three remaining districts covered by the monitoring programme are concerned, the concentrations of *THM* compounds were dependent on their relative location with respect to the water blending plant, which is in this case, **Doha Water Blending Complex**. At **Al-Andalus**, which is the nearest to the water blending plant, the average total concentration of *THM* compounds was found to be **16.67** ± **3.29** µg/L, ranging from a maximum of **23.38** µg/L to a minimum of **12.40** µg/L. The average residual chlorine concentration at this district was **0.79** ± **0.08** mg/L, ranging from a maximum of **0.90** mg/L to a minimum of

0.60 mg/L. When the above concentrations are compared to those present at the pumping station (20.42 ± 6.84 µg/L) of the blending complex, it could be concluded that on average very little change in these concentrations had occurred by the time the drinking water reach the consumer at the **Al-Andalus** district, despite the depletion in residual chlorine.

The concentrations of *THM* compounds at **Al-Jabriya** districts were much higher. The average total *THM* compounds concentration at this district, which is some distance further compared to **Al-Andalus** district, was found to be **37.51** ± **5.99** µg/L, ranging from a maximum of **53.98** µg/L, to a minimum of **28.44** µg/L. The corresponding average residual chlorine in this district was **0.63** ± **0.08** mg/L, ranging from a maximum of **0.80** mg/L to minimum of **0.50** mg/L. It is clear that, due to increased contact time and with the presence of sufficient source of chlorine, further formation of *THM* compounds occur in drinking water as it is being distributed to consumers at **Al-Jabriya** district.

At **Hawalli** district, which is situated next to **Al-Jabriya** district, a very similar situation exists. The average total *THM* compounds concentration was found to be **34.31** ± **7.09** µg/L, ranging from a maximum of **44.82** µg/L to a minimum of **17.86** µg/L. However, the average residual chlorine found in the drinking water at this district was much lower at **0.10** ± **0.06** mg/L, ranging from a maximum of **0.20** mg/L to a minimum of **0.01** mg/L. The reason for this depletion of residual chlorine must be due to the much higher drinking water consumption which is a characteristic of this district and the absence of suitable organic precursors necessary to sustain further *THM* compounds formation.

5. The most dominant *THM* compound is bromoform. On an overall basis, the relative contribution of these compounds to the average total concentration were as follows: bromoform **75.3%**, dibromochloromethane **16.6%**, bromodichloromethane **6.1%** and finally chloroform **2.0%**. The contribution of bromoform varied from a maximum of **83.5%** at **Keifan** to a minimum of **57.5%** at **Al-Andalus**.

6. The effect of temperature on *THM* compounds formation was very profound. During summer season, which is characterized by higher water temperatures, the average total *THM* compounds concentration at **Al-Jabriya** district was found to be **75.94** ± **4.30** µg/L, ranging from a maximum of **81.25** µg/L to a minimum of **67.72** µg/L. The above total concentration is more than double that found at the same district during the spring season.

7. The influence of contact time was clearly demonstrated. The further the district is from the water blending complex the higher the *THM* compounds concentrations are, provided there is a source of chlorine and suitable organic precursors.

CHAPTER SEVEN

GENERAL CONCLUSIONS & RECOMMENDATIONS

7.1 GENERAL CONCLUSIONS

Based on the research work covered in this study, the following general conclusions could be made :-

1. The level of *THM* compounds concentrations and corresponding mass loads during the chlorination of sea water utilised by the **Power Generation & Water Production Stations** have been clearly shown to be dependent on the type of the chlorination practice being followed and relevant existing conditions. It was clearly demonstrated that the concentrations of *THM* compounds were substantially higher during shock chlorination practice, which is characterized by high chlorine dosage, as compared to continuous chlorination practice. Therefore, the level of chlorine dosage was of paramount importance in determining the extent of formation of *THM* compounds during the chlorination of sea water. The second parameter which was clearly shown to have a great impact on the formation of these compounds is the temperature of sea water. A substantial dependence which is exponential in nature was evident. The influence of other parameters which are believed to affect the extent of formation of *THM* compounds during the chlorination of sea water, such as *TOC* and *pH*, could not be investigated in a manner which is capable of determining such influence. The concentration of total organic carbon (*TOC*) was assumed to be within a narrow range, whilst the *pH* of sea water was monitored but found to be nearly constant. Contact time was in part determined by plant design but also influenced by the distance that separates the plants from the chlorination site. The further the plant was from the chlorination site, the greater the formation of *THM* compounds due to higher contact times.

2. Despite the substantial formation of *THM* compounds during chlorination of sea water, only very little of this formation ends up in the distilled water produced by the distillation plant. During continuous chlorination practice and based on a distillation plant with product capacity of 27276 m^3/day (*6 MIGPD*), only **3.45** g/h remains in the distillate product (*equivalent to a concentration of* ***3.05*** µg/L) out of a total *THM* compounds formation in cooling sea water of **203.08** g/h (*equivalent*

to a concentration of 22.19 µg/L). This means that out of the initial total formation of *THM* compounds in sea water only **1.69%** is retained in the distillate product. The remaining *THM* compounds (**98.31%**) were either discharged back to the sea (**65.96%**) with the excess cooling sea water not required by the distillation plant or rejected to the atmosphere by the distillation plant (**32.34%**) along with the vent gases. Out of the total *THM* compounds (**69.12** g/h) entering the distillation unit *via* the make-up feed, **95.01%** is removed by the distillation process due to the combined effect of deareation and direct and cascade stage venting, confirming the high removal efficiency of Multi-Stage Flash (*MSF*) distillation plants. The above removal efficiency drops slightly to about **92.60%** during shock chlorination practice resulting in distillate total *THM* compounds mass load of **9.01** g/h and corresponding concentration of **7.89** µg/L.

3. Out of the total *THM* compounds formed as by-products due to the chlorination of sea water entering the distillation plants, about 66% is discharged back to the sea. Based on a total installed distillation plants capacity of 240 MIGPD and considering the mass loads of *THM* compounds being formed in sea water utilised by the power generation plants, it is estimated that an annual *THM* compounds mass of 50 ton is discharged back to the sea. This is a considerable discharge and could very possibly constitute a very serious environmental problem. However, it has been shown by previous studies and inferred from this study that relatively high concentrations of *THM* compounds are evident only at or very near to the discharge structures of the stations and that a rather fast dilution process occurs which is highly influenced by the hydrodynamic conditions prevalent at the concerned sites. Having said this the existing concentrations of *THM* compounds could still result in adverse impact as far as the ecology of the marine environment is concerned.

4. Bromoform is by far the most dominant *THM* compound formed as a result of the sea water chlorination process. This dominance is clearly due to the high concentration of bromide ions in sea water. The dominance of bromoform is sustained, though to a slightly lesser extent, as far as the distilled water produced by the distillation plants is concerned. The percentage relative contributions of bromoform to the total *THM* compounds present were **94.4%** and **87.5%**, respectively. In addition, distilled water was also characterized by relatively high presence of (**12.5%**) bromodichloromethane.

5. The addition of organic chemical compounds, such as anti-scalents and anti-foams, does not contribute in any significant degree to the formation of *THM* compounds during continuous chlorination practice. However, it has been shown that this addition could contribute to further *THM* compounds formation during shock chlorination practice, when excess chlorine is available to sustain further formation.

6. The main source of *THM* compounds formation in drinking water in *Kuwait*, is due to the chlorination of the blended water produced by mixing distilled water with brackish water at the water blending complex. An average overall total concentration of **20.42** ± **6.84** µg/L was detected in the water leaving **Doha Water Blending Complex**. This formation of *THM* compounds commences from the moment the chlorination process starts and remains active well after the water leaves the boundaries of the water blending complex. Factors which greatly influence the extent of this formation include chlorine dosage and temperature of the water being chlorinated.

7. The overall average total concentration of *THM* compounds in drinking water, based on the monitoring programme which covered five different districts in *Kuwait* city during the spring season, was found to be **40.04** ± **20.97** µg/L. The maximum total *THM* compounds concentration encountered was **92.35** µg/L, while the minimum total concentration detected was **8.39** µg/L. Factors which enhanced *THM* compounds formation include higher chlorine dosage, high temperatures and increased contact time.

8. The most dominant *THM* compound present in drinking water is bromoform. On an overall basis, the relative contributions of *THM* compounds to the average total concentration were as follows : bromoform **75.3%**, dibromochloromethane **16.6%**, bromodichloromethane **6.1%** and chloroform **2.0%**. The relative contribution of bromoform varied from a maximum of **83.5%** to a minimum of **57.5%**.

9. The concentrations of *THM* compounds in drinking water originating from distilled water which had undergone recarbonation treatment, in order to stabilizes the water aggressive nature and thus minimize corrosion, were found to be considerably higher than when the water had not been treated. It is very clear that the carbon dioxide extracted from the vent gases of the distillation plants and utilised in the recarbonation treatment, is very rich in *THM* compounds. Although some of these compounds tend to escape during the recarbonation treatment, substantial amounts will end up in the treated distilled water.

10. Based on the monitoring programme, it is evident that the total concentration of *THM* compounds in drinking water always remained below the maximum contamination limit (*MCL*) set by the **United States Environmental Protection Agency** (*USEPA*) of **100** µg/L. However, it must be said that during the summer season when the water temperature is at its maximum, *THM* compounds total concentration could approach this value if the chlorination process at the blending plant is not controlled within certain limits. Such control must be enhanced considerably if the intention is to keep with the trend of reducing the *MCL* with the intention of lowering it eventually to **1.00** µg/L.

11. Due to the absence of sufficient valid data to warrant the classification of brominated trihalomethane compounds as carcinogens and the level of concentrations encountered in drinking water, it is unlikely that the presence of these compounds presents any adverse impact on public health. Obviously, a concrete conclusion regarding this matter must await a much more comprehensive survey which must cover all of *Kuwait* and for a much more extended period of time than has been the case in this study. Furthermore, associated studies exploring the toxicity and carcinogenity of brominated trihalomethane compounds, with special emphasis on bromoform, must also be performed.

7.2 RECOMMENDATIONS

This research work has highlighted the need to investigate in depth certain aspects which are related to subjects which were tackled in this study. Recommendations for future work are listed below :-

1. The monitoring of the formation of *THM* compounds due to the chlorination of sea water prior to entry to distillation plants needs to be extended to cover more efficient plants. The most important aspect of design here concerned the impact of enhanced deareation of make-up feed on the fate and removal of these compounds and the impact of the method of chlorination.

2. The impact of the chlorine source of the chlorination practice on the formation of *THM* compounds should be investigated. The chlorination process could utilise either chlorine gas, sodium hypochlorite or chlorine generated by electrolysing sea water. The impact of each of these methods of chlorination needs to be closely investigated.

3. The optimization of the chlorination of sea water needs to be attained. This optimization must ensure the efficient operation of the distillation plants and power generation plants in addition to minimising the adverse impact of any discharges on the marine environment. Alternative methods of chlorination such as targeted chlorination should be investigated and factors which determine optimum chlorination dosage and dosage frequencies should be studied in depth.

4. The formation and fate of *THM* compounds during chlorination of feed water for other desalination processes, such as reverse osmosis, should be investigated. It is suspected that their fate could be substantially different to that witnessed in the case of *MSF* distillation.

5. The chlorination of water at the water blending plant has been shown to be the most important factor in determining the level of *THM* compounds in drinking water.

It is therefore very important to optimize this chlorination process with the aim of producing safe drinking water by ensuring that the water is disinfectant but at the same time contains the least concentrations of *THM* compounds. All pertinent factors must be covered ranging from consumption rates to water quality variations to seasonal variations to blending plant and distribution network design considerations.

6. A more comprehensive monitoring of the level of *THM* compounds present in drinking water in all districts in *Kuwait* should be performed. This survey should ideally be for a whole year and should simultaneously cover all production centres and districts.

7. The process design of the recarbonation plants needs to be altered. The aim should be to remove *THM* compounds from the carbon dioxide gas utilised for the recarbonation process prior to making contact with the treated water.

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APPENDIX I

Distillation Unit Stage-By-Stage *THM* Compounds Behaviour Analysis

The equilibrium concentrations of gases or volatile liquids in water depends on the temperature of the phases, the total pressure, and the molecular interactions occurring between the dissolved substance (*solute*) and water (*solvent*). At equilibrium, the concentration or partial pressure of a substance in the gas phase is proportional to its concentration in the liquid phase according to *Henry's Law*. When the gas phase is ideal, the total pressure of a gaseous mixture is the sum of the partial pressures of the individual components according to *Dalton's Law*. Combining these two laws, we obtain

$$Y_i = \frac{X_i H}{P} \qquad \text{Eq. I1}$$

where $\mathbf{Y}_i$ is the mole fraction of component i in the gas phase , $\mathbf{X}_i$ is the mole fraction of component i in the liquid phase, **H** is *Henry's Law* constant and **P** is the total pressure.

Knowing *Henry's Law* constant and the total pressure permits computation of the equilibrium concentration in vapour-liquid systems. Qualitatively, the greater *Henry's Law* constant, the more easily a compound can be removed from solution. Conversely, a low value for *Henry's Law* constant indicates high solubility of the compound in water.

In general, increasing the system temperature will increase the partial pressure of a component in the vapour or gas phase in equilibrium with a specified solution concentration. From a thermodynamic analysis, the temperature dependence of the *Henry's Law* constant can be modeled by a *vant Hoffe-type* relation, given in integrated form by

$$Ln\, H = \frac{-a}{T} + b \qquad \text{Eq. I2}$$

where **H** is *Henry's Law* constant in atm (*liquid volume / gas volume*), **T** is temperature in degrees Kelvin, and **a & b** are empirical constants.

It has already been explained that each stage of the *MSF* distillation unit will have its own saturation temperature and corresponding saturation pressure. In other words, each stage will be at a distinct equilibrium condition. Once the superheated flashing brine is introduced into the stage, it boils and releases excess vapour and thus reaching the stage existing equilibrium temperature.

The brine entering the flash chamber of stage **No. 1** is the recirculating brine exiting the brine heater. In every stage, the brine flashes resulting in released vapour moving upwards, passing through the demisters and then mostly condenses on the surfaces of the condenser tubes as distillate product. The conditions at the vapour space above the demisters are characterized by slightly lower temperatures and pressures. A small percentage (about 2% by volume) of the released vapour along with a host of non-condensable gases like CO_2, O_2 and NH_3 is sucked by the venting system of the stage. The now concentrated brine passes into the next stage and the above process is repeated. In the final stage, a small portion of the remaining brine is discarded as blowdown brine, in order to maintain salt balance. The remaining part is mixed with incoming make-up feed necessary to compensate for the lost distillate and blowdown brine flows. Deareation of the make-up flow is carried out prior to the mixing in the deareation chamber which forms an integral part of the last stage. The mixed stream, which is now called the recirculating brine, is then sent to the condenser tubes of the heat gain section and heat input section for gradual heating before it repeats the above flashing cycle in successive stages. The extracted vent gases are then sent to a number of condensers where the water vapour content is condensed and retrieved. The collected condensate is then added to the distillation unit distillate product.

Based on the equilibrium conditions existing in each stage, a prediction of the stage behaviour of each *THM* compound can be made. This could be done based on the relationship given by *Eq. I1*. The mass loads of each *THM* compound released as vapour, condensed along with distillate, left in the flashing brine and extracted by the venting system can all be computed.

A derivation of the mathematical relationships which enable such predictions are given below :-

The concentration of component ***i*** in the flashing brine $\mathbf{(C_{fi})_n}$ entering the flash chamber of stage **No. *n*** is given by *Eq. I3*.

$$(C_{fi})_n = \frac{(m_{fi})_n \, (D_f)_n \, (10^3)}{(MF)_n} \qquad \text{Eq. I3}$$

where $\mathbf{(m_{fi})_1}$ is the mass load of component **i** in the flash chamber of stage **No. 1** is taken to be identical to the measured mass load of component **i** in the recirculating brine leaving the last stage. This assumes that there is no loss in the total *THM* compounds mass load and that there is no conversion from one compound to another, while the recirculating brine is being heated inside the condenser tubes. This assumption is considered quite valid as no phase change occurs while the brine flows inside the condenser tubes.

The mole fraction of component ***i*** in the liquid phase (*brine below demister*) in flash chamber of stage **No. n**, $(X_{bi})_n$, is given by *Eq. I4* below :-

$$(X_{bi})_n = \frac{(C_{fi})_n \, (MW)_w}{(MW)_i \, (D_f)_n \, (10^6)} = \frac{(m_{fi})_n \, (MW)_w}{(MF)_n \, (MW)_i \, (10^3)} \qquad \text{Eq. I4}$$

The mole fraction of component ***i*** in the vapour phase below the demister, $\mathbf{(Y_{bi})_n}$ is given by *Eq. I5* :

$$(Y_{bi})_n = \frac{(X_{bi})_n \, (H_{bi})_n}{(P_b)_n} = \frac{(m_{fi})_n \, (MW)_w \, (H_{bi})_n}{(MF)_n \, (MW)_i \, (P_b)_n \, (10^3)} \qquad \text{Eq. I5}$$

where **$(H_{bi})_n$** is *Henry's Law* constant of component ***i*** below the demister in stage ***n*** at temperature **$(T_b)_n$** and is given by *Eq. I6* below :-

$$Ln\,(H_{bi})_n = \frac{-\,a}{(T_b)_n} + b \qquad \text{Eq. I6}$$

The vapour pressure of component ***i*** below the demister in the flash chamber of stage **No. *n* $(p_{bi})_n$** is given by *Eq. I7* below :-

$$(p_{bi})_n = (Y_{bi})_n\,(P_b)_n = \frac{(m_{fi})_n\,(MW)_w\,(H_{bi})_n}{(MF)_n\,(MW)_i\,(10^3)} \qquad \text{Eq. I7}$$

The concentration of component ***i*** in the vapour phase below the demister in a stage is given by *Eq. I8* below :-

$$(C_{vi})_n = \frac{(p_{bi})_n\,(MW)_i\,(10^6)}{(R)\,(T_{vb})_n} = \frac{(m_{fi})_n\,(MW)_w\,(H_{bi})_n\,(10^3)}{(MF)_n\,(R)\,(T_{vb})_n} \qquad \text{Eq. I8}$$

The mass load of component ***i*** in the vapour released in flash chamber of stage **No. *n* is** given by *Eq. I9* below :-

$$(m_{vi})_n = \frac{(C_{vi})_n\,(V_v)_n}{10^3} = \frac{(m_{fi})_n\,(V_v)_n\,(MW)_w\,(H_{bi})_n}{(MF)_n\,(R)\,(T_{vb})_n} \qquad \text{Eq. I9}$$

where **$(V_v)_n$** is the vapour volume release rate in the flash chamber of stage **No. *n*** in m^3/h and is given by *Eq. I10* below :-

$$(V_v)_n = \frac{(0.974)\,(T_{vb})_n\,(MD)_n}{(P_b)_n\,(10^3)} \qquad \text{Eq. I10}$$

The distillate production of stage **No. *n*, $(MD)_n$**, is given by *Eq. I11* below :-

$$(MD)_n = \frac{(MF)_n \, (C_p)_n \, (T_{f(n)} - T_{f(n-1)})}{L_n} \qquad \text{Eq. I11}$$

The vapour pressure of component ***i*** in the vapour phase above the demister in the flash chamber of stage **No.*n*, $(p_{ai})_n$**, is given by *Eq. I12* below :-

$$(p_{ai})_n = \frac{(C_{vi})_n \, (R) \, (T_{va})_n}{(MW)_i \, (10^6)} = \frac{(m_{fi})_n \, (MW)_w \, (H_{bi})_n \, (T_{va})_n}{(MF)_n \, (T_{vb})_n \, (MW)_i \, (10^3)} \qquad \text{Eq. I12}$$

The mole fraction of component ***i*** in the vapour phase above the demisters in the flash chamber of stage **No.*n*, $(Y_{ai})_n$**, is given by *Eq. I13* below :-

$$(Y_{ai})_n = \frac{(m_{fi})_n \, (MW)_w \, (H_{bi})_n \, (T_{va})_n}{(MF)_n \, (T_{vb})_n \, (MW)_i \, (P_a)_n \, (10^3)} \qquad \text{Eq. I13}$$

The mole fraction of component ***i*** in the distillate produced in the flash chamber of stage **No.n, $(X_{di})_n$**, is given by *Eq. I14* below :-

$$(X_{ai})_n = \frac{(Y_{ai})_n \, (P_a)_n}{(H_{ai})_n} = \frac{(m_{fi})_n \, (MW)_w \, (H_{bi})_n \, (T_{va})_n}{(MF)_n \, (T_{vb})_n \, (MW)_i \, (H_{ai})_n \, (10^3)} \qquad \text{Eq. I14}$$

The value for *Henry's Law* constant, for component *i*, in the vapour space above the demister in the flash chamber of stage **No.*n*, $(H_{ai})_n$**, is given by *Eq. I15* below:-

$$Ln \, (H_{ai})_n = \frac{-a}{(T_a)_n} + b \qquad \text{Eq. I15}$$

The concentration of component **i** in the distillate product of the flash chamber of stage **No. n, $(C_{di})_n$**, is given by *Eq. I16* below :-

$$(C_{di})_n = \frac{(X_{ai})_n\ (MW)_i\ (D_d)_n\ (10^6)}{(MW)_w} = \frac{(m_{fi})_n\ (H_{bi})_n\ (T_{va})_n\ (D_{di})_n\ (10^3)}{(MF)_n\ (H_{ai})_n\ (T_{vb})_n} \qquad \text{Eq. I16}$$

The mass load of component **i** in the distillate product of the flash chamber of stage **No. n, (m_{di})**, is given by *Eq. I17* below :-

$$(m_{di})_n = \frac{(C_{di})_n\ (MD)_n}{(D_d)_n\ (10^3)} = \frac{(m_{fi})_n\ (H_{bi})_n\ (T_{va})_n\ (MD)_n}{(MF)_n\ (H_{ai})_n\ (T_{vb})_n} \qquad \text{Eq. I17}$$

The mass load of component **i** in the vent gases of the flash chamber of stage **No. n, $(m_{gi})_n$**, is the difference between the mass load of the component **i** in the released vapour and that present in the distillate product. This mass load can be calculated according to *Eq. I18* below :-

$$(m_{gi})_n = \frac{(m_{fi})_n\ (H_{bi})_n}{(MF)_n\ (T_{vb})_n} \left(\frac{(MW)_w\ (V_v)_n}{R} - \frac{(T_{va})_n\ (MD)_n}{(H_{ai})_n} \right) \qquad \text{Eq. I18}$$

The concentration of component **i** in the vent gases leaving the flash chamber of stage **No. n, $(C_{gi})_n$**, is given by *Eq. I19* below :-

$$(C_{gi})_n = \frac{(m_{gi})_n\ (10^3)}{(V_g)_n} \qquad \text{Eq. I19}$$

The volumetric flow rate of vent gases **$(V_{gi})_n$** in a stage can be calculated by subtracting the volumetric flow rate of distillate produced from the volumetric flow rate of released vapour.

The vapour pressure of component **i** in the vent condenser $\mathbf{p_{gi}}$ can be determined from *Eq. I20* below :-

$$p_{gi} = \frac{(C_{gi})\ (R)\ (T_{vc})}{(MW)_i\ (10^6)} \qquad \text{Eq. I20}$$

$\mathbf{(C_{gi})}$ is the concentration of component **i** in the vent gases reaching the vent condenser and is determined by calculating the total mass load of component **i** in the vent gases and the total volume of vapour which is contained in the vent gases reaching the vent condenser. This volume is the summation of the difference between the released vapour and the distillate product in every stage.

The mole fraction of component **i** in the vapour phase in the vent condenser, $\mathbf{(Y_{ci})}$, is given by *Eq. I21* below :-

$$Y_{ci} = \frac{p_{gi}}{P_c} \qquad \text{Eq. I21}$$

The mole fraction of component **i** in the liquid phase (*condensate*) collected from the vent condenser, $\mathbf{X_{ci}}$, is given by *Eq. I22* below :-

$$X_{ci} = \frac{(Y_{ci})(P_c)}{(H_{ci})} \qquad \text{Eq. I22}$$

where $\mathbf{H_{ci}}$ is *Henry's Law* constant at $\mathbf{T_c}$ and is determined from *Eq. I23* below :-

$$Ln\ (H_{ci}) = \frac{-\ a}{T_c} + b \qquad \text{Eq. I23}$$

The concentration of component **i** in the condensate from the vent condenser, $\mathbf{C_{ci}}$, can be determined from *Eq. I24* below :-

$$C_{ci} = \frac{(X_{ci})\ (MW)_i\ (D_c)\ (10^6)}{(MW)_w} \qquad \text{Eq. I24}$$

Finally, the mass load of component **i** in the condensate from the vent condenser, $\mathbf{m_{ci}}$, which is normally added to the distillate product can be determined from *Eq. I.25* below :-

$$m_{ci} = \frac{(C_{ci})\ (MV)}{(D_c)\ (10^3)} \qquad \text{Eq.I25}$$

The total mass flow rate of the vent gases, **MV**, is the summation of the difference in each stage between the mass flow rate of the released vapour and the distillate mass flow rate.