*FIGURES*

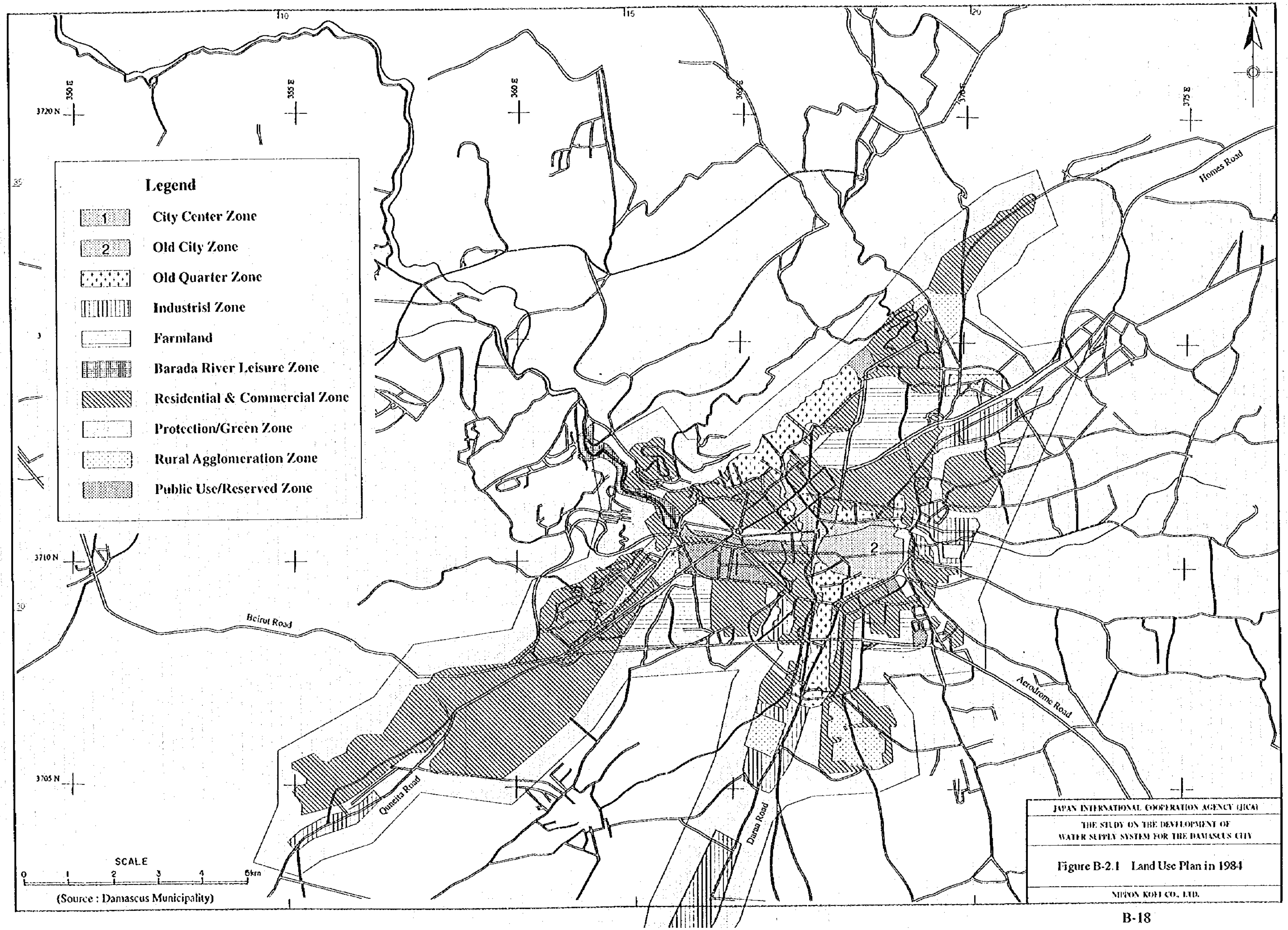
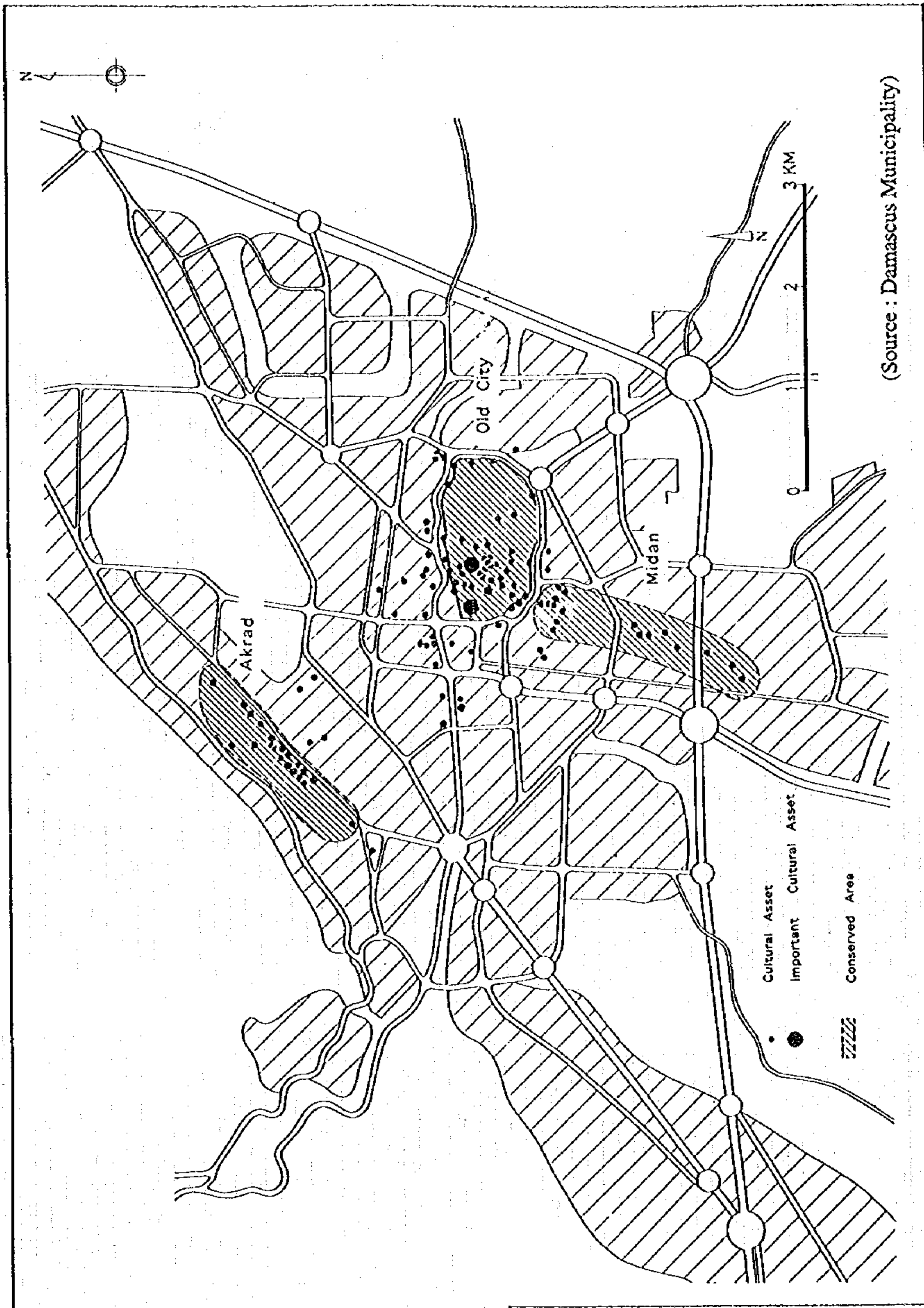


Figure B-2.1 Land Use Plan in 1984



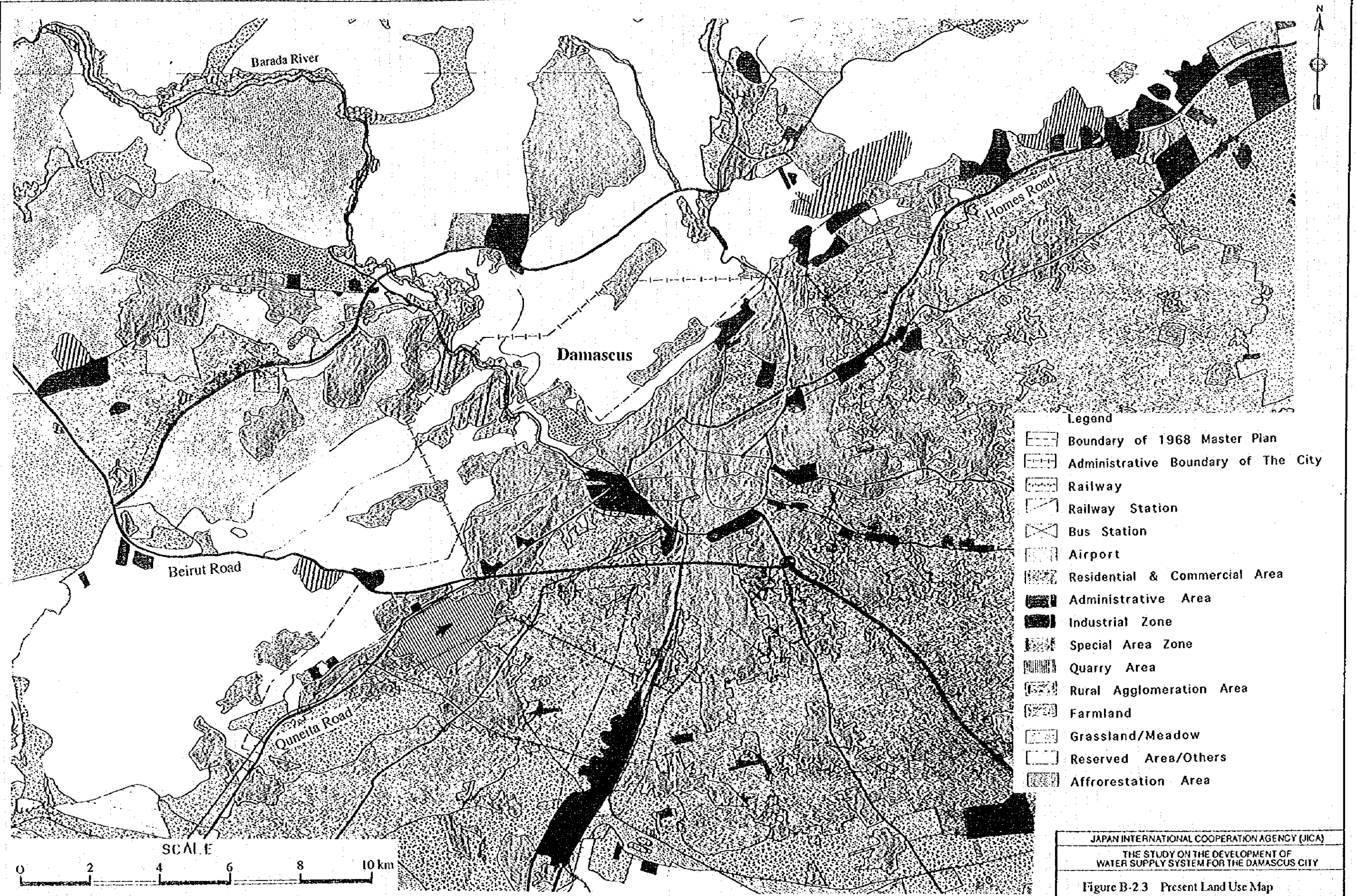

(Source : Damascus Municipality)

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

Figure B-2.2 Location of Cultural Asset

NIPPON KOEI CO., LTD.



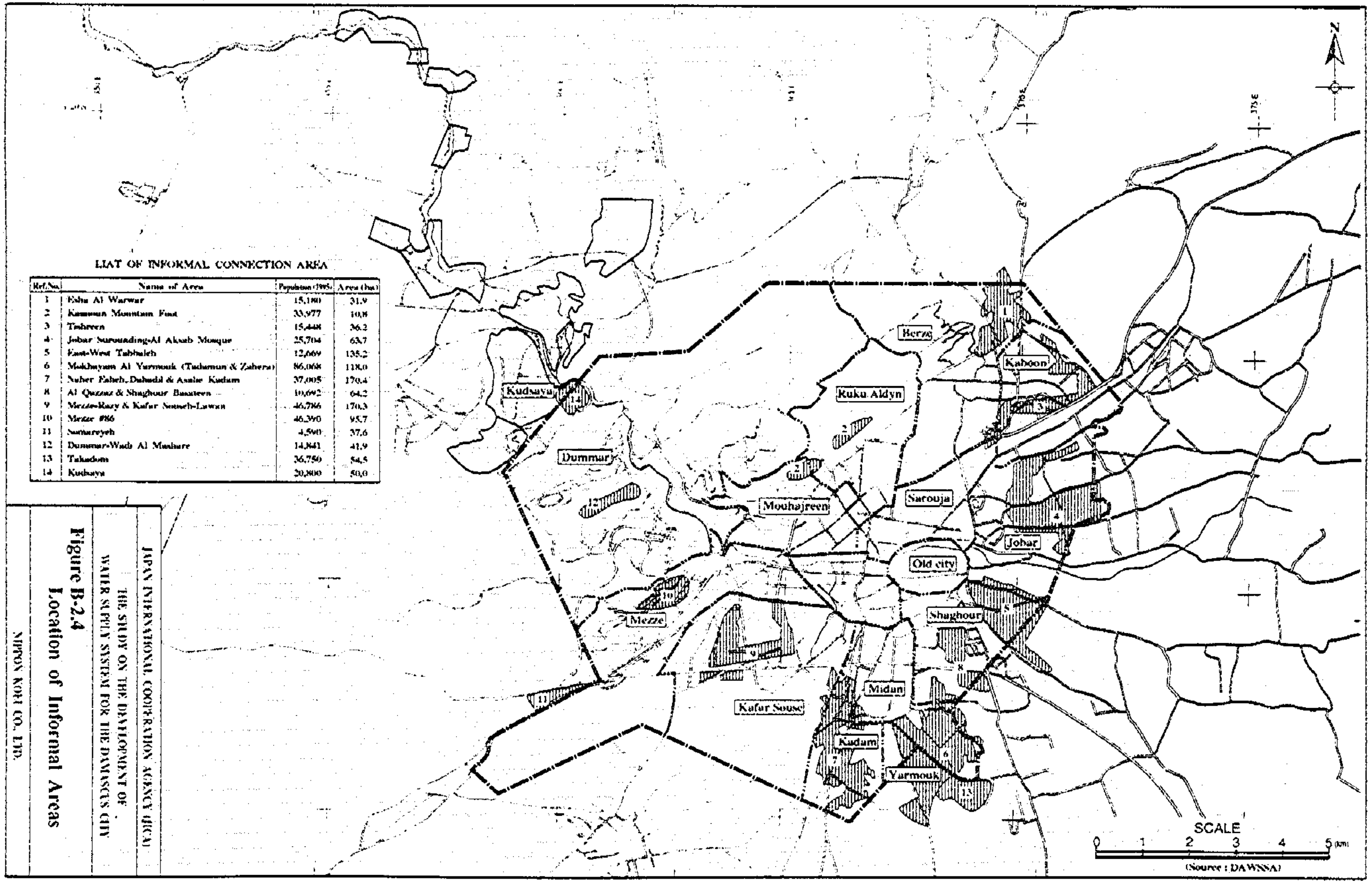

(Source : Damascus Municipality)

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

Figure B-2.3 Present Land Use Map

NIPPON KOEI CO., LTD.




LIAT OF INFORMAL CONNECTION AREA

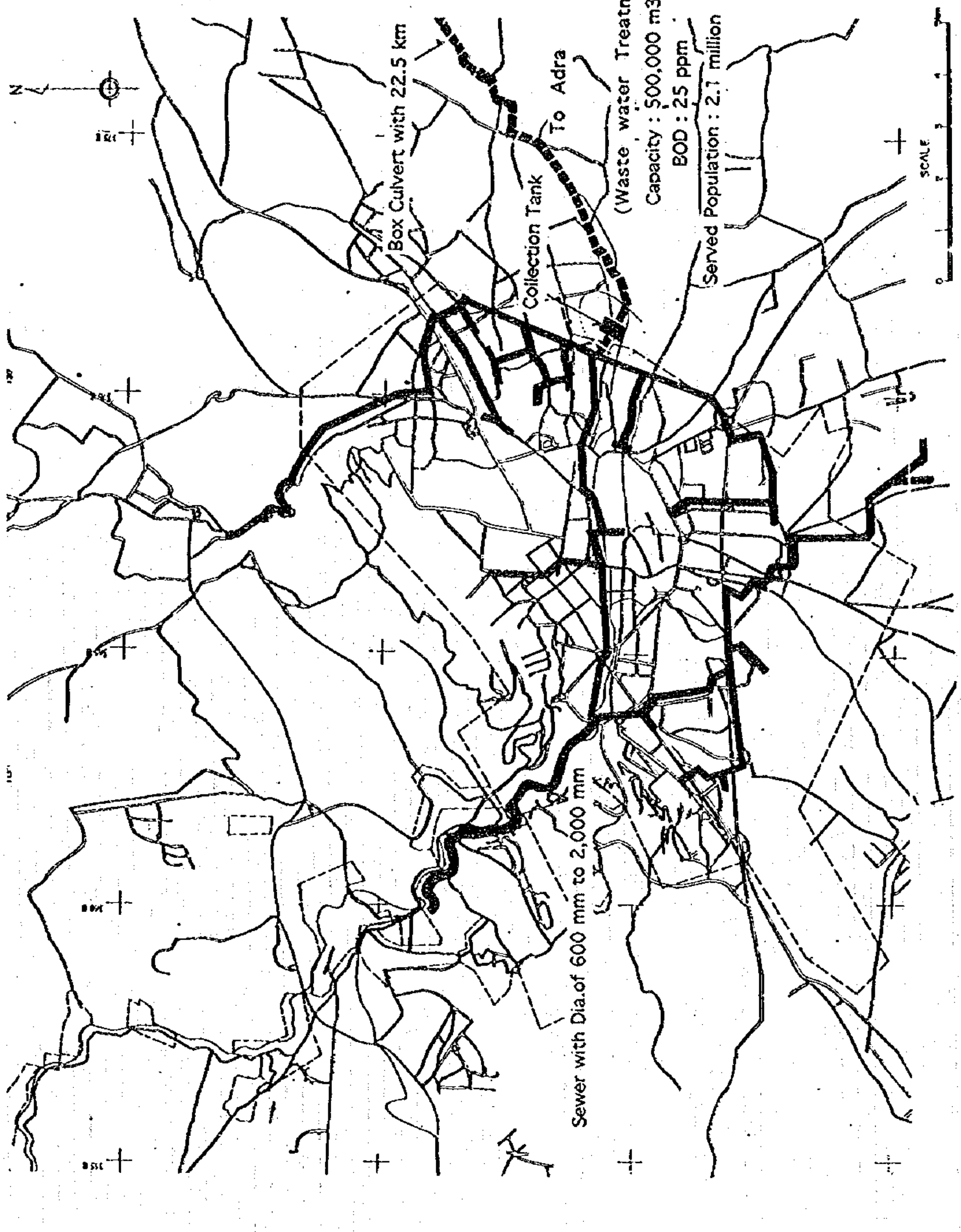
| Ref.No. | Name of Area | Population (1995) | Area (ha) |
|---|---|---|---|
| 1 | Esha Al Warwar | 15,180 | 31.9 |
| 2 | Kassoun Mountain Foot | 33,977 | 10.8 |
| 3 | Teshreen | 15,448 | 36.2 |
| 4 | Jobar Surounding-Al Akaab Mosque | 25,704 | 63.7 |
| 5 | East-West Tabbaleh | 12,069 | 135.2 |
| 6 | Mokhayam Al Yarmouk (Tadaman & Zahera) | 86,068 | 118.0 |
| 7 | Naher Esheh, Dahadil & Asaile Kadam | 37,005 | 170.4 |
| 8 | Al Quzzaz & Shaghour Basateen | 10,692 | 64.2 |
| 9 | Mezze-Razy & Kafar Souseh-Lawan | 46,786 | 170.3 |
| 10 | Mezze #86 | 46,390 | 95.7 |
| 11 | Sumareyeh | 4,590 | 37.6 |
| 12 | Dummar-Wadi Al Mashare | 14,841 | 41.9 |
| 13 | Takadom | 36,750 | 54.5 |
| 14 | Kudsaya | 20,800 | 50.0 |

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF
WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

**Figure B-2.4**
**Location of Informal Areas**

NIPPON KOEI CO., LTD.

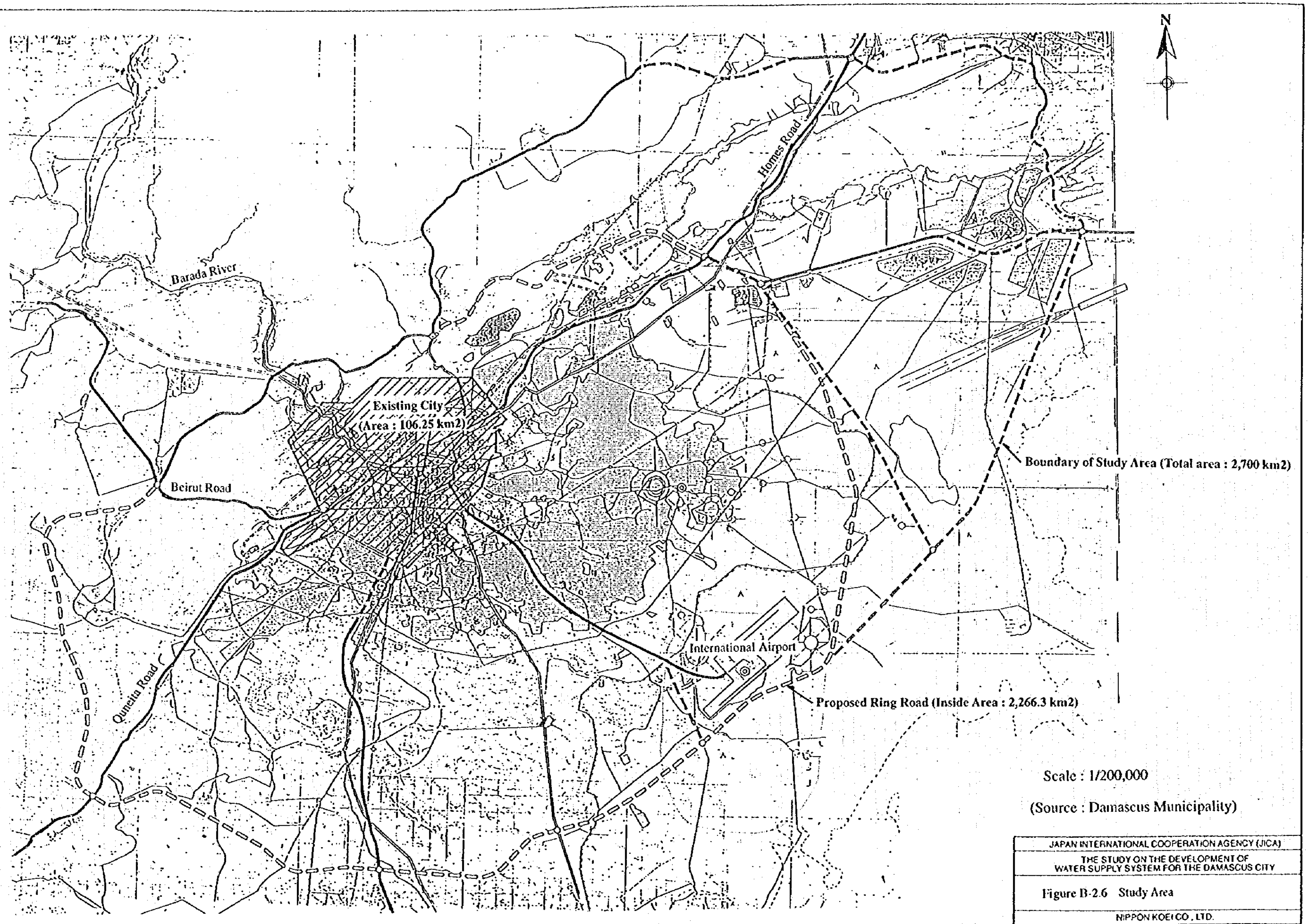



JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

Figure B-2.5 **Plan of Sewerage**

NIPPON KOEI CO., LTD.

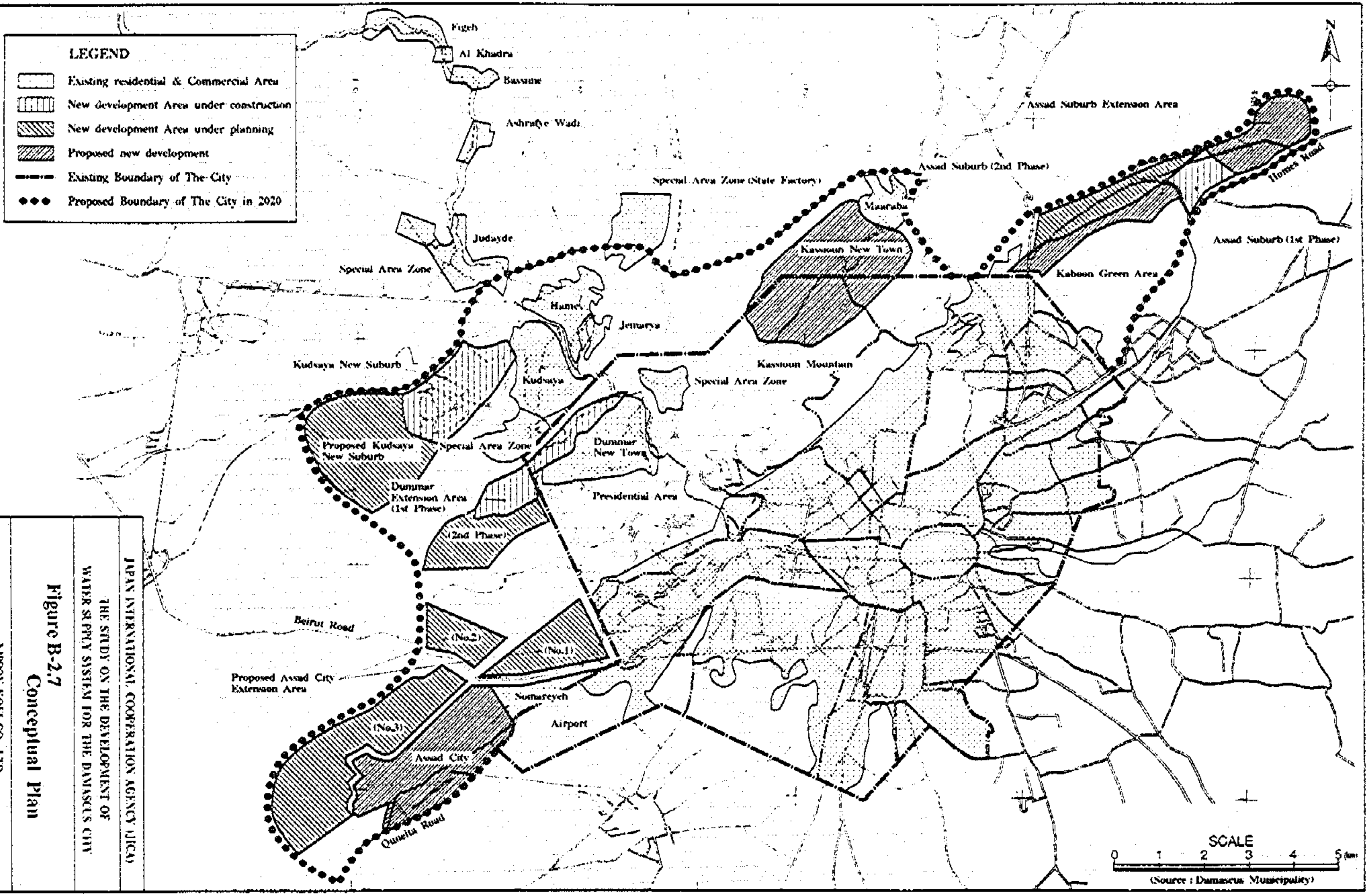



JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

Figure B-2.6 Study Area

NIPPON KOEI CO., LTD.

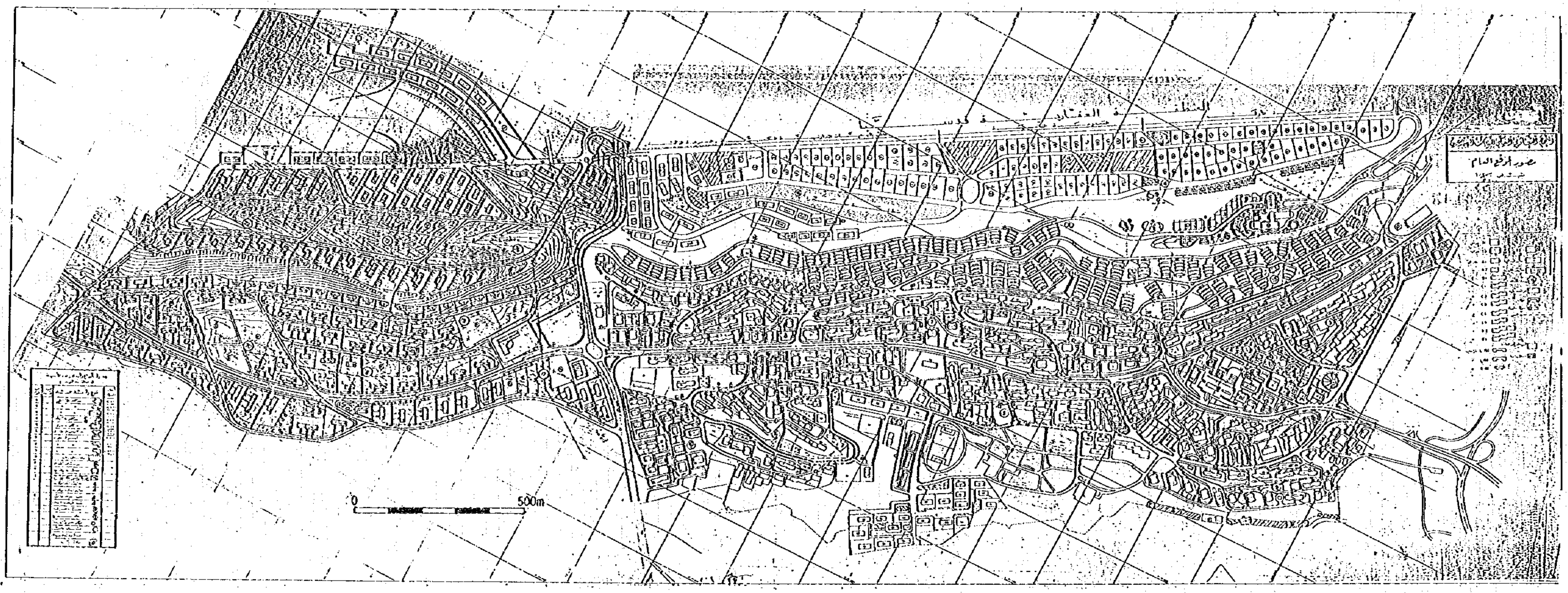



JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

**Figure B-2.7**
**Conceptual Plan**

NIPPON KOEI CO., LTD.



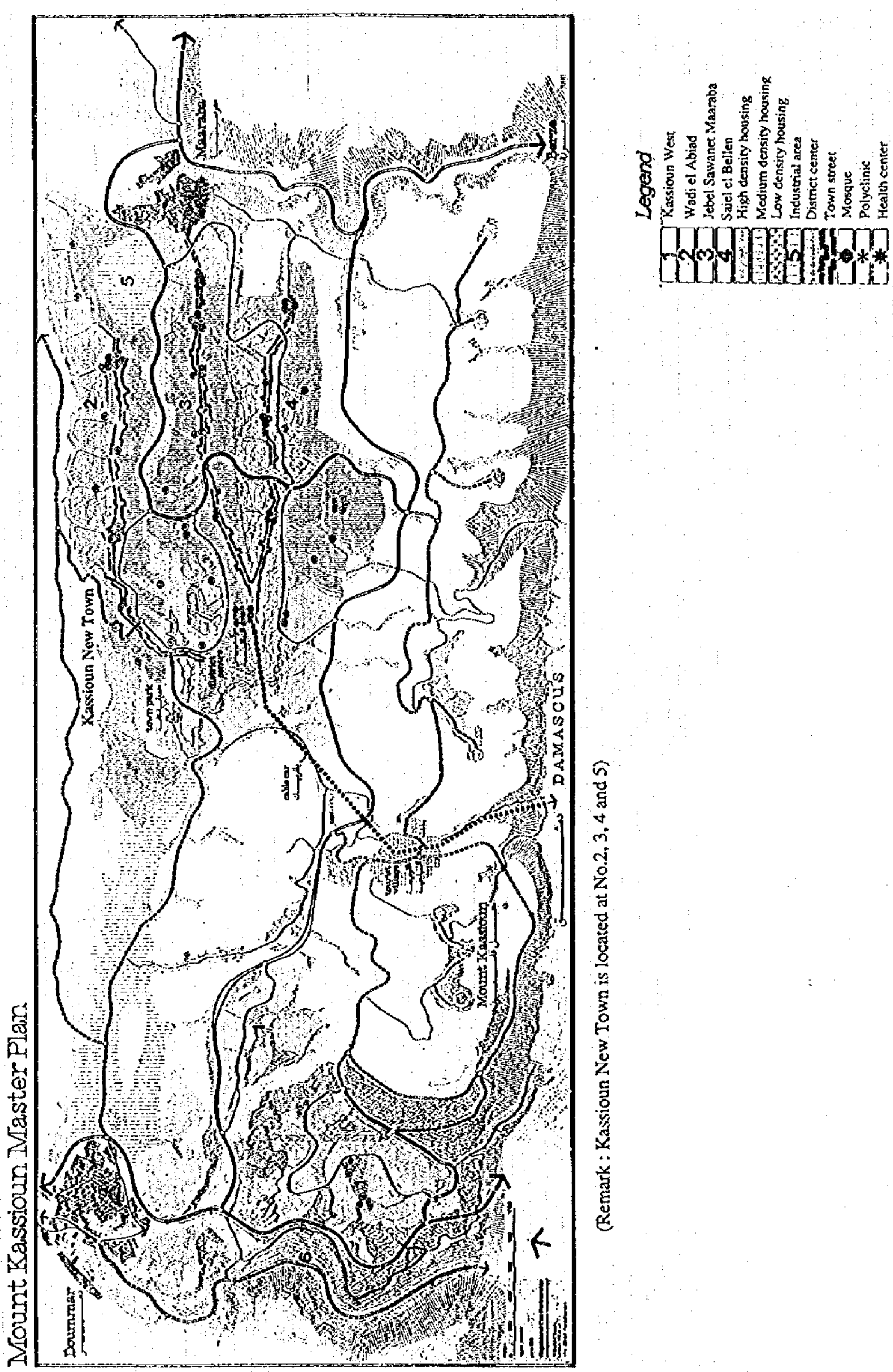

(Source : Damascus Municipality)

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

Figure B-2.8 Dummar Extension Area (1st Phase)

NIPPON KOEI CO., LTD.




(Remark : Kassioun New Town is located at No.2, 3, 4 and 5)

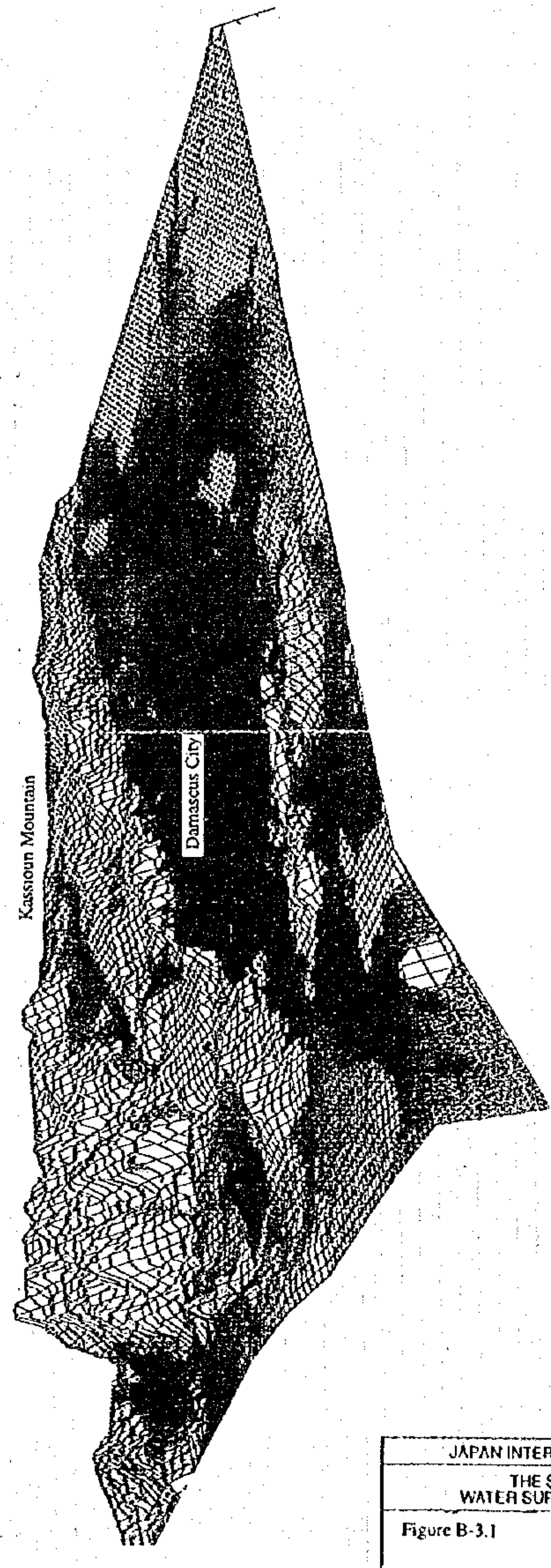
(Source : Damascus Municipality)

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

Figure B-2.9 Kassioun New Town

NIPPON KOEI CO., LTD.



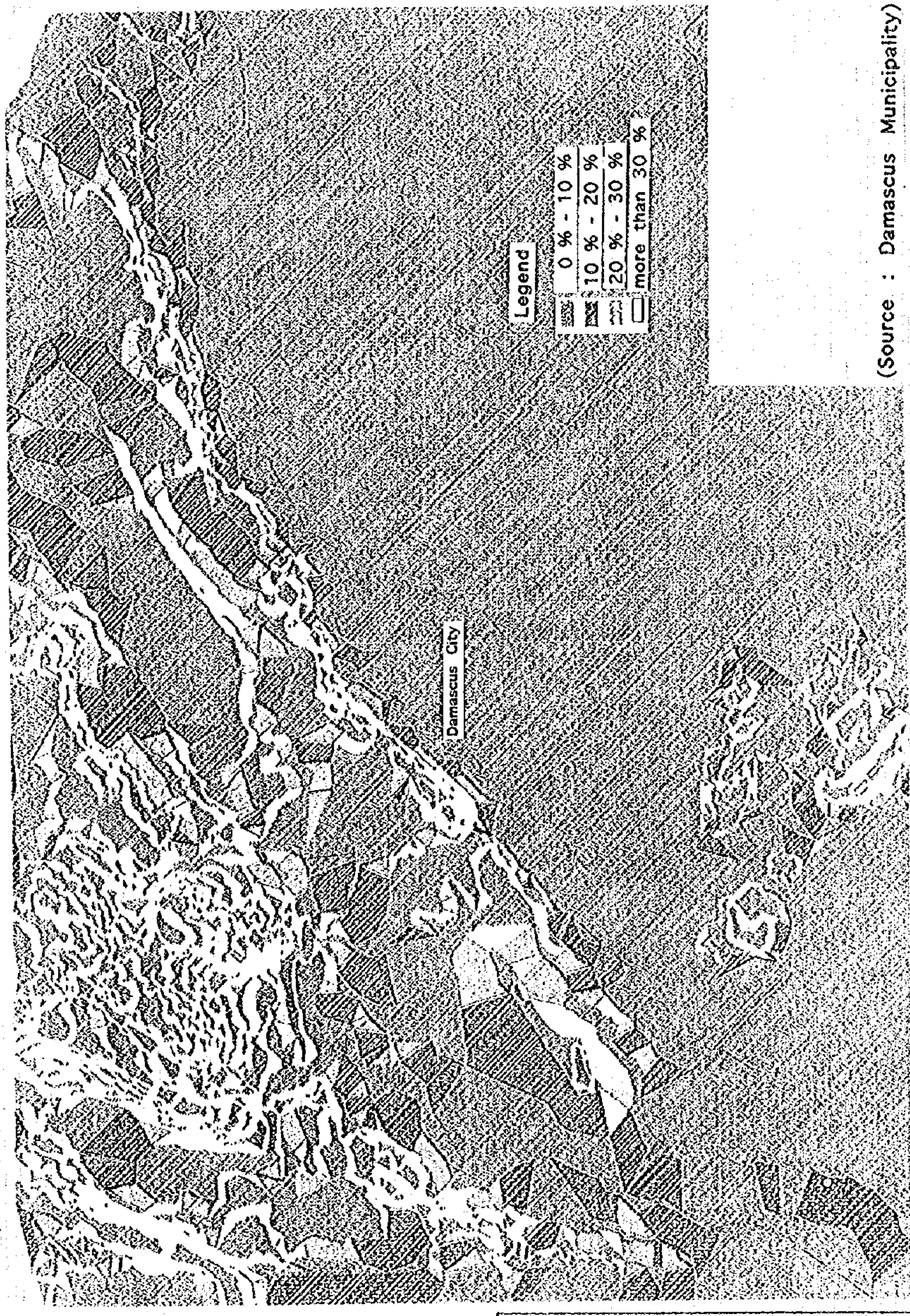

(Source : Damascus Municipality)

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF
WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

Figure B-3.1 **3D Topographic Map**

NIPPON KOEI CO., LTD.



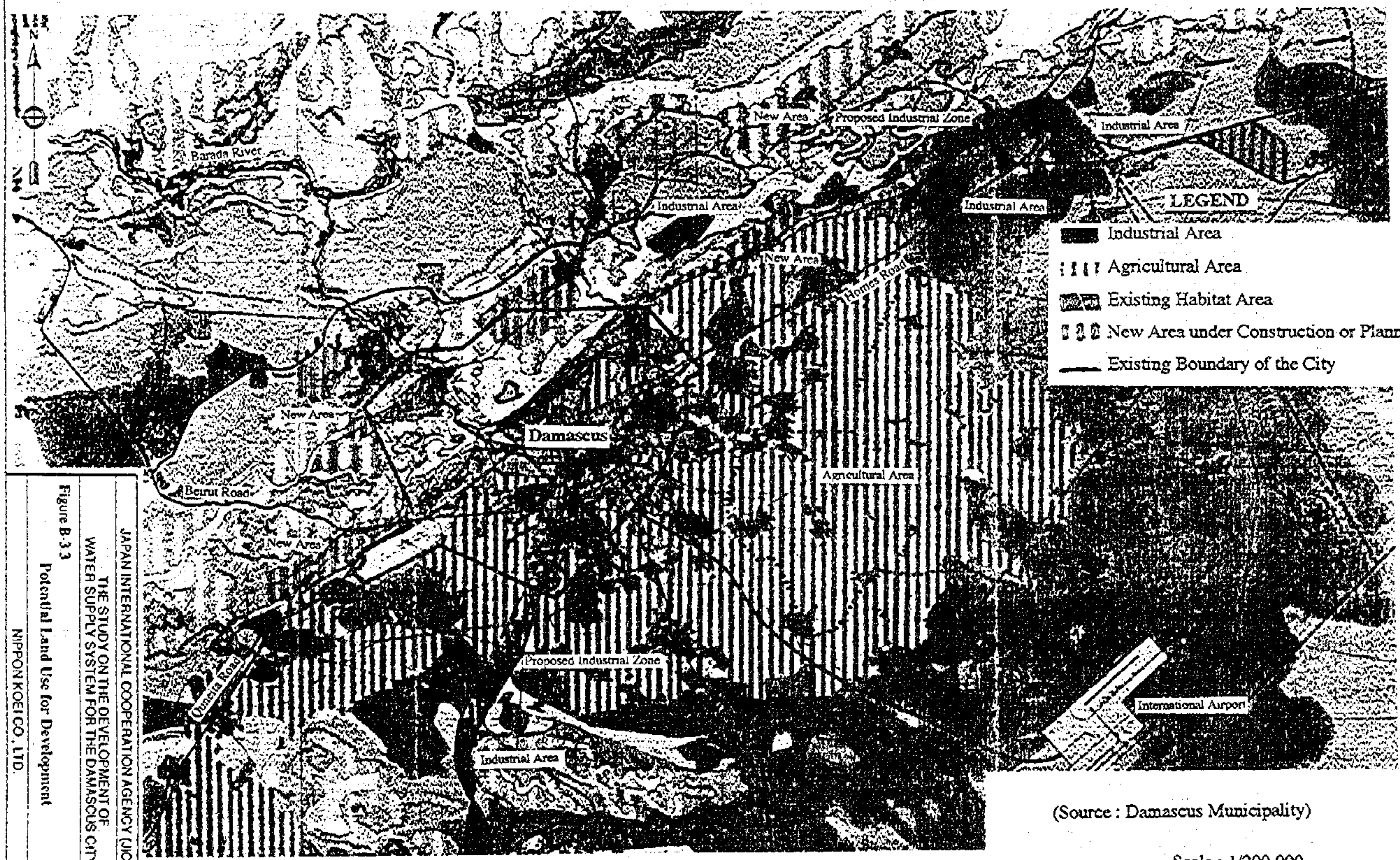

(Source : Damascus Municipality)

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

Figure B-3.2 **Slope Inclines**

NIPPON KOEI CO., LTD.




JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

THE STUDY ON THE DEVELOPMENT OF
WATER SUPPLY SYSTEM FOR THE DAMASCUS CITY

Figure B-3.3

**Potential Land Use for Development**

NIPPON KOEI CO., LTD.

# APPENDIX C

# WATER RESOURCES

APPENDIX C

WATER RESOURCES

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

## 1. INTRODUCTION

This water resources supporting report makes part of the Master Plan for the Damascus City Water Supply and Sewerage Authority (DAWSSA). The supply to the population served by DAWSSA is currently derived from a large spring of Ain el Figeh located 15 km from the city, a wellfield surrounding the spring of Barada 30 km from the city and wellfields within the city.

The existing sources are unable to meet the present requirements or the forecast needs during the Master Plan period 1996 to 2015. Significant new unused water resources have not been found in this Study. Nonetheless, with careful management and the optimum utilization of existing and new sources the seasonal water deficits may be reduced and for most of the year eliminated for the period up to 2005.

The Appendix provides the background setting of the area in terms of topography, geology, meteorology, hydrology and hydrogeology. The current water utilization by both DAWSSA and the other competing interests are outlined.

The Appendix describes twelve water resources schemes and then selects those that are suitable technically, economically and politically for inclusion into the Water Supply Master Plan. Recommendations are produced for the design of the schemes and also for water resources studies and data collection that should be implemented during the Master Plan period.

## 2. PRESENT CONDITION

### 2.1 Physical Setting

#### 2.2.1 Topography

Damascus is located in the southwest of the Syrian Arab Republic at approximately latitude 33°30' north and longitude 36°20' east. The study area covers the approximate limit of the city urban area, however for the water resources investigation consideration is made of the whole of the surface water catchment of the Barada and Awaj rivers upstream from the mountain front, the groundwater catchments of the main springs and the Damascus wellfields, Figure C-2.1. Topographically the area may be divided into two main domains; the Anti-Lebanon mountains and the El-Arab Trough.

The City of Damascus has grown up at the point where the Barada River leaves the boundary mountain belt of the Anti-Lebanon and flows east onto the plain of the El Arab Trough. The urban area, at 650 to 750 m above sea level, has covered the alluvial fan created by the river, and now has spread up the valley of the Barada River, on to the slopes of Kassioun and other hills to the west of the city. To the south east the land forms a plain that gently dips to the closed depressions of lakes Ateibeh and Hijaneh at just about 600 m above sea level.

The mountain belt consists of a series of parallel ridges and intermontane valleys running south-west to north-east. The ridges are cut by deeply incised wadis such as the valley of the Barada River. The principal ridges are Ash Sheikh (2814 m), Ash Shaqif (2466 m) Kassioun to Ash Sharqieh (1515 m) and Shir Mansour (1883 m).

The mountain areas have developed karstic features such as swallow holes, caves, springs and drainless basins. They are formed in the massive dolomites and limestones of the Jurassic and Upper Cretaceous, and are most strongly developed in areas of tectonic fracturing or at the interface between Turonian Limestone and other lithologies. Most of the springs are small and ephemeral but a few have a very large catchments and are perennial, notable springs from a water supply perspective are those at Barada and Figeh.

Intermontane areas such as the Zabadani Plain and Sednaya Plain occupy the synclines or grabens within the fold mountain belt. They are flat bottomed 2 to 10 km wide and may be up to 35 km long with the valley floor at an elevation of 800 to 1400 m. The valley sides are have talus and alluvial fans, and their floors are often the site of ancient lake beds.

To the south of the Damascus Basin lie volcanic plateau comprising the Golan Heights and the slopes of Jabel Arab (Jabel Druze). The area has a distinctive landform of small truncated conical hills and the rough land surface of black basalt.

### 2.1.2 Geology

#### (1) Stratigraphy

Within the study area there are outcrops of rocks from the Jurassic to the Quaternary age, Figures C-2.2a and C-2.2b. The Jurassic and Cretaceous rocks are mainly limestones and dolomites. The Jurassic rocks outcrop in the western part of the study area forming Jabel esh Sheikh (Mount Hermon) and the mountains west of the Zabadani Valley. A small outcrop occurs on the eastern side of the valley north of Zabadani. The Lower Cretaceous consist of three formations, the lowest is a sandstone, this overlain by chalky limestone and the upper is a sandy clay and marls. The Lower Cretaceous rocks occur throughout the area except where the Jurassic rocks are exposed. Upper Cretaceous formations lie conformably on the earlier sediments. The Cenomanian & Turonian dolomitic limestones outcrop over large areas on Kassioun Mountain and the Jabel ash Shaqif mountain range. The Senonian rocks have a more limited outcrop on the flanks of the main mountains. Their lithologies range from limestones to clays. The Paleogene is represented by predominantly argillaceous deposits, marls and clays. The outcrops are in the area between the Jabel ash Shaqif and the Kassioun mountain ranges. A narrow outcrop, but of hydrogeological significance, runs along the south western side of Jabel ash Shaqif mountain range. The Neogene comprises mainly terrestrial formations, conglomerates and sandstones with some limestones and marls. The strata lies unconformably over the Paleogene in an outcrop band running parallel and to the north west of Kassioun Mountain. The Quaternary comprises great a thickness of alluvial, proluvial (colluvial), lacustrine limestones and basalts to the south west of Kassioun. Thinner accumulations of Quaternary lacustrine and proluvium (colluvium) are found in the inter-montane basins of Sednaya and Zabadani. Basalts occur at the surface to the south of the study area and extend north in the subsurface beneath Neogene rocks and interdigitate with the Quaternary sediments stretching as far north as the southern suburbs of Damascus. A fuller description of the stratigraphy and rock types is presented in Table C-2.1.

#### (2) Structure

The regional structure is made up of two domains the Anti-Lebanon fold mountains and the El-Arab Trough. The Damascus Fault marks the boundary between these two areas. Within the Anti-Lebanon mountains the Jurassic to Paleogene strata have been folded and faulted by the northward movement of the Arabian plate. The folds form an echelon pattern with their axis running north east to south west. The limbs of the folds are asymmetrical with the north western limbs dip at 60 to 80°, while the south eastern facing limbs dip at only 35 to 40°. The form of the geological structure is reflected in the mountains with the anticlines forming the ranges while the synclines the inter-montane basins. The Jurassic has in addition been faulted into horst and graben blocks, especially in the area west of the Zabadani Valley. Neogene strata lies unconformably on the Paleogene tending to be found within the synclines of the fold structure. The folding within these rocks is more gentle than in the older strata. The geological cross section shows these structural elements, Figure C-2.3.

The Damascus Fault marks the edge of the El-Arab Trough. The Paleogene strata has been downthrown in a complex synsedimentary graben structure (Damascus Depression), Figure C-2.4. This has been infilled with Neogene and Quaternary terrestrial sediments and numerous Miocene to Quaternary lava flows. The deepest part of the graben is adjacent to the Damascus Fault where the Neogene and younger rocks have been proved to be over 800 m thick and the total throw of the fault, 1000 m.

Within the Anti-Lebanon region the existence of extensive faulting and fracturing is important in the development of the karstic drainage. The position of faults often dictate the location of springs or sink holes. The highly fractured zone associated with the Figeh fault probably has led to the existence of the important spring at this location.

## 2.2 Climate and Meteorology

### 2.2.1 Climate

The climate of the Damascus Plains is Mediterranean, characterized by hot dry summers from April to October and a humid cold winter from November to March. The main features of the climate in Damascus are depicted in Table C-2.2 The winter period is influenced by cyclones from the west bringing rain and overcast conditions, or anticyclones from Siberia with cold cloudless weather. In the summer an anticyclone develops over the eastern Mediterranean which prevents the westerly tracking cyclones from reaching Syria. The summer season is dominated by cloudless hot weather with dry south westerly winds.

The mountains above 2000 m experience very cold wet winters and mild dry summers. Precipitation falls mainly as snow which remains on the high ground throughout the winter. The annual snow melt occurs during the spring months. A climatological summary of Zabadani, meteorology station located at an altitude of 1160 m, is presented in Table C-2.3.

### 2.2.2 Meteorology

#### (1) Meteorological network

The earliest records that exist for the study area date from 1918 when the precipitation record for Mezze in Damascus was started. The network of monitoring locations grew especially in the 1950's and 1960's and currently there are a total of 60 stations, of these 41 are rainfall stations and the remaining 19 are climatological.

The majority of the network is operated by the Meteorological Department. The pertinent station details for all the network within the Damascus Basin, are shown in Table C-2.4 and their positions plotted in Figure C-2.5. The currently DAWSSA uses the data from 3 rainfall stations, operated by themselves, and two climatological stations. The five stations are in the groundwater catchment of Figeh Spring and are used for water resources assessments and flow predictions. DAWSSA plan to expand the network with two new remotely operated climatological stations.

#### (2) Precipitation

The rainfall is non uniform over the water resources study area and very variable from year to year. In the mountains the rainfall may exceed 1200 mm above an altitude of 2000 m, while on the plain east of Damascus the rainfall is less than 100 mm. The areal distribution of rainfall is depicted in Figure C-2.6.

The annual rainfall from the DAWSSA stations is presented in Table C-2.5. The stations all receive similar volumes of precipitation, the long term average ranging from 485 mm at Madaya to 565 mm at Sergaya, the long term average rainfall from all five stations is 512 mm. Figure C-2.7 depicts the annual rainfall pattern from 1956 to 1995. There is a great variability in the amount of rainfall between years with some drought years such as 1959/60 receiving 227 mm and exceptionally wet years such as 1991/92 with over 925 mm of precipitation. The five year running mean rainfall marked on the graph does not show any systematic pattern of either change in the total amount of rainfall though the last 28 years, or evidence of any systematic cyclicity in rainfall. Similarly, examination of both the 3 year and 7 year running means also do not show any systematic changes in the characteristics of the precipitation. The variability in the rainfall is depicted in Figure C-2.8 which illustrates the percentage of time that particular rainfall quantities may be expected. The median rainfall (50%) is 508 mm which is very similar to the mean of 512 mm. The rainfall expected in dry years is particularly important in the estimation of water resource availability. The frequency pattern approximates to a statistically normal distribution, but with slight deviations at the extreme conditions (above 95% and below

5%). In the tails of the distribution the precipitation is higher than may be anticipated from the normal distribution. The precipitation and frequency information is shown in the following table.

| Probability | Percentage of Years | Rainfall Exceeds (mm) |
|---|---|---|
| 1 year in 20 | 5 | 760 |
| 1 year in 10 | 10 | 700 |
| 1 year in 4 | 25 | 600 |
| 1 year in 2 | 50 | 508 |
| 3 years in 4 | 75 | 408 |
| 9 years in 10 | 90 | 309 |
| 19 years in 20 | 95 | 270 |

(3) Evaporation

The potential evaporation ranges from 1000 mm in the high mountains to 1500 mm to the east of Damascus. The actual annual mean evaporation, Figure C-2.9, is however limited by water availability. In the mountains it is about 350 mm whereas in the plains it may be only 100 mm, these values representing 45% and 100% of the total rainfall respectively. In the Damascus Ghouta the evaporation is up to 380 mm which is far greater than the rainfall, the extra water lost to the atmosphere is due to the groundwater table being unconfined and close to the surface. Evapotranspiration peaks in the period May to August and is at a minimum from December to January.

## 2.3 Hydrology of Surface Water

### 2.3.1 Drainage

(1) Barada River

The Barada is a relatively short river, its full length being no more that 80 km. It rises in the mountains north west of Damascus fed by major springs, then it cuts through the mountains to emerge onto the Damascus alluvial fan, Figure C-2.10. Before the intensive use of river water for irrigation flow extended to Lake Ateibeh. In the catchment above Barada spring the stream flow is ephemeral, occurring only during the snow melt and at times of the rains. From the spring the stream flows south through a broad valley to Tekieh. At this point the Barada veers to the east and has cut a narrow gorge like valley perpendicular to the geological structure. A tributary stream from Wadi Karren joins the main river at this point. Both the Barada and Wadi Karren have dams in the vicinity. The Wadi Karren dam is an anti-flood dam (a capacity of 1.6 MCM) while the dam on the main river has only one day of supply to serve a small hydroelectric plant. Along the gorge the flow is augmented by groundwater inflows and springs, most notably Figeh Spring, 19 km downstream from Barada Spring. The last gauging point on the river before it is divided at El Hame. Upon emerging from the gorge through the mountains the main channel of the river is split into 7 major channels at different elevations, these spread out over the alluvial fan where all the water is lost by infiltration and abstraction. The flow in each of the channels was apportioned by a traditional system of weirs and sluices. The system was operated by the MOI and ensured that a fixed ratio of flows was maintained between each of the canals. Table C-2.6 itemizes each of the canals and the percentage of the total river flow at that El Hame, and the detail of the canals within Damascus are marked on Figure C-2.11. The traditional system has not been used for at least ten years, there not being enough water in the river to permit the regular subdivision of flows. The whole flow of the river is distributed amongst the irrigation channels of the Ghouta. Under natural conditions prior to widespread irrigation the Barada discharged into the perennial Lake Ateibeh. The last time that this location was fed by the Barada was 1969. Presently all the water is used or evaporates before reaching the bed of lake which is now dry.

(2) Awaj River

The second important river in the vicinity of Damascus is the Awaj River. The river starts from springs that rise from the eastern side of Jebel esh Sheikh. There are two main tributaries, the Janani that is fed by the Beit Jenn spring and, to the north, the Sebrani fed by the springs of Rimeh and Arneh. The headwaters of both tributaries are confined to steep sided valleys which are gorge like in places. Upon leaving the mountains they spread across their alluvial fans and join near Saasaa. The streams are perennial within the mountains, but upon reaching the alluvial fan the flow is lost to irrigation canals and bed infiltration and they become ephemeral over some reaches. Downstream from Saasaa the river flow is directed into major irrigation canals, the principle ones being the; Derani, Kanakri, Zakiani and Darhabani Canals. The internal drainage basin for the river is Lake Hijaneh, under current conditions of intensive water usage the flow barely extend to the Kisweh and does not reach the dry lake basin some 30 km further down channel.

2.3.2 Hydrological Network

The oldest flow gauging stations in the Damascus Basin are on the Awaj and Barada rivers. A station was established at Om el Sharatit on the Awaj in 1930, and at El Hame on the Barada in the following year. Three minor wadis also have gauging stations, Mnin, Liwa and Khanfes, the remainder of the stations are on the two permanent rivers in the basin. Special investigations have resulted in the rehabilitated the existing stations and the added new stations. For example, in 1974 an additional 14 stations were installed in the Awaj/Barada Basin as part of a Soviet project. A second wave of instrumentation was undertaken in another Soviet project when 7 extra gauging stations where built in 1982/3. The data from a network of 31 when 7 extra gauging stations where built in 1982/3. The data from a network of 31 hydrological permanent and many temporary stations were monitored during the early to mid 1980's as part of the Barada & Awaj Study the data from this exercise and the previous data is reported in Lengiprovodkhoz 1986. The details of the these measurement stations are to be found in Table C-2.7. The gauging stations are operated by the MOI. The size of the network has been pared paired down to 14 locations in the last 10 years, some of the streams are now perennially dry, other water courses have been modified and generally less intensive monitoring is undertaken.

DAWSSA measures the flow at two locations by current metering a section of the stream. Over the course of a year about 80 measurements are made. Measurements at Ramleh are to represent the flow from Barada Springs and those at Tekieh the flow leaving the Zabadani Valley. The stream from Ramleh to Tekieh during the winter season receives contributions from small streams draining the Zabadani Valley, while in the summer period water is abstracted for irrigation by hundreds of small pumps. Consequently the winter flow at Tekieh is higher than Ramleh and the summer flow lower. DAWSSA estimates that at certain times of the year up to 1 $m^3/s$ is lost between the spring and Tekieh. As part of the development of the Barada wellfield it is planned to modify the outflow channel to enable the flow to be measured at Barada its self.

### 2.3.3 Stream Flow

The Barada spring produces a perennial streamflow with a long term natural discharge of about 3.1 $m^3/s$. The river is augmented by the overflow from the Figeh Spring which has a long term average discharge of 7.7 $m^3/s$. In the past, the natural flow of the Barada left the mountains was 14.0 $m^3/s$, due to infiltration losses and evaporation this fell to 6.7 $m^3/s$ by the time the water reached Lake Ateibeh. The Awaj River at Saasaa has a natural discharge of about 4.7 $m^3/s$.

The annual hydrographs on all water courses are dominated by the influence of the seasonal spring snow melt and spring inflows. There is a discharge peak in late spring followed by a recession of flows until September to November when the rainy season increases the flow again. The rainfall quantity is highly variable year to year, this is reflected in the large differences in hydrographs for both rivers, as is illustrated in Figures C-2.12a,b,c. The mean annual flow for the Barada at El Hame is 11 $m^3/s$ with a 95% probability of a discharge of over 7.2 $m^3/s$, and 5% probability of a discharge of over 18 $m^3/s$. While for the Awaj at Om Sharatiet a mean flow of 4.5 $m^3/s$ with a 95% probability of exceeding 1.5 $m^3/s$, and a 5% probability of a discharge over 12.7 $m^3/s$. These probabilities may be found illustrated on Figure C-2.13

The flow characteristics of the river systems have been dramatically modified by the man's activities, the diversion of spring water into the water supply network and the diversion of surface flows into irrigation canals and the return of waste water into the rivers. Details of the contemporary and non-natural flows of the stream is discussed in the section C-2.6 on water utilization.

## 2.4 Hydrology of Springs

### 2.4.1 General

The main perennial springs in the area are karstic issuing from the Turonian and Jurassic rocks to the north west of Damascus. Minor springs which are often seasonal occur throughout the area, however, the vast majority of the discharge is derived from just two spring sources, Figeh and Barada. The springs, incorporated into the MOI monitoring network, generally with yields of more than 10 l/s (864 $m^3/d$), are listed in Table C-2.8 and their locations marked on Figure C-2.14.

### 2.4.2 Data Availability

The springs of the Barada & Awaj Basin are well documented. The MOI has monitoring the monthly discharge from Barada from 1931 to 1993 and many other springs since 1974. DAWSSA and its predecessor organizations has been responsible for the measurement of discharge of Figeh Spring, daily records began in 1941. A comprehensive survey of springs undertaken in the early 1980's catalogued over 200 springs recording location, elevation, discharge, water temperature and electrical conductivity, (Lengiprovodkhoz 1986). The MOI has made the records of annual mean flow for the hydrologic years 1984-85 to 1994-95 (11 years) and records of monthly flows for 1985-86 to 1993-94 (9 years), available for this study. The discharge information of springs prior to 1984-85 is published in Lengiprovodkhoz (1986).

### 2.4.3 Data Analysis Methodology

A study of the discharge data has been undertaken to characterize the present behavior of springs. In addition changes to in the spring response with time are identified. The present behavior is net of all human activities that tend to modify the recharge or groundwater flow in the spring catchment, for example abstraction or changes in land use. The analysis has looked at the spring data in four ways; to see the relationship between spring flow and rainfall on an annual basis, to look for long term trends in spring flow, to look at monthly spring flow, and, the summer recession of flows has been investigated. The methodologies adopted are outlined in the following sections

(1) Annual spring flow

The annual spring flow in a spring is a function of the recharge in the catchment. A measure of the recharge is taken as the mean rainfall measured by DAWSSA's network of five meteorological stations in the Figeh catchment. It is assumed that the ratio of rainfall quantities received over the Barada and Awaj catchment at different places does not vary greatly from year to year and so rainfall in Figeh area can be taken as a measure of the rainfall elsewhere, though it will be higher or lower depending on its topographic position. The flow of a spring may not be the result of the rainfall in only the preceding hydrological year. In most springs the winter recharge to the catchment is not all discharged by the spring in the following summer, some of the water will be discharged in the subsequent years. To incorporate this process in the analysis the rainfall in any one year was weighted to take into account the antecedent rainfall conditions. The weighting was done with the equation C.1.

$$R_w = a\,R_1 + b\,R_2 + c\,R_3 \qquad \text{(C.1)}$$

Where:

| | |
|---|---|
| $R_w$ | Weighted rainfall in mm |
| $R_1$ | Rainfall averaged from 5 stations for current year, in mm |
| $R_2$ | Rainfall averaged from 5 stations for 1 year ago in mm |
| $R_3$ | Rainfall averaged from 5 stations for 2 years ago in mm |
| a,b,c | Empirical factors that sum to 1 |

The relationship between rainfall and spring flow has been established for the principal springs in the area. A weighted rainfall is plotted against the total yield of the spring and one or more regression equations calculated to describe the behavior, the equations have the form given in C.2. The spring data for the period 1985 to 1995 was used to represent the current spring behavior.

$$Q = m\,R_w + c \qquad \text{(C.2)}$$

Where:

| | |
|---|---|
| $R_w$ | Weighted rainfall in mm |
| Q | Average annual discharge in l/s |
| m | Factor |
| c | Constant |

As has been demonstrated in the meteorological section the rainfall probability distribution is statistically approximately a normal distribution. For this reason it is possible to use the mean rainfall and various other rainfall reoccurrence frequencies to calculate the minimum spring flow for any given level of probability.

(2) Long term trends of spring flow

Changes in spring response are identifiable for springs where there is a long data record and a relationship between rainfall and discharge. A plot of cumulative rainfall against cumulative volume of discharge falls on a straight line if there are no changes to the spring behavior. A deviation from a straight line is due to changes that effect the water flow in the spring catchment. A simple relationship between rainfall and flow is given by the gradient of the line, or factor 'm' in equation C.3.

$$\sum_{n=start}^{n=end} Q = m \sum_{n=start}^{n=end} R \qquad \text{(C.3)}$$

(3) Monthly spring flow

Analysis of the monthly flows from Barada Spring, Figeh, Beit Jenn and Tabibiyeh have been undertaken. The differing approaches to the problem mainly reflect the length and reliability of the data record.

The springs at Beit Jenn and Tabibiyeh have short duration of record, but moreover, they are far removed from the Figeh catchment rainfall stations. Although annual flows can correlate well between these springs and the Figeh catchment the monthly spring flows do not. Use of data from local rain gauges also does not give a good description of how the springs behave. The reasons for this may be multifarious; data reliability problems, local positioning of the gauge, and possibly most likely, that the gauge is recording the precipitation on the lee side of the mountain, whereas the Figeh catchment gauges measure on the windward side of the mountain range.

The spring flow for each month has therefore not been predicted as such but statistically described. The discharge in any month is not normally distributed like annual volumes but has a strong positive skew. Prior to determining the mean and standard deviation of the data the skewness was removed by taking the logarithms of the flow. Once the statistical parameters are determined they are converted back to flows in standard linear units. The determination of various discharge probabilities is undertaken with the mean and standard deviation, expressing the probability in terms of the number of standard deviation units. These can be found in tabulated forms of the normal curve is statistics texts. For example a 1.64 standard deviation from the mean value covers is equivalent to a 95% or 5% probability. A probability level of 1 in 20 years or 95% has been arbiter chosen as the design criteria for the Master Plan. To determine the average monthly flow for a particular month that will be exceeded 95% of the years equation C-4 can be used. Since the standard deviation has been calculated from data with a logarithmic transformation applied to it the equation reflects the necessary adjustment required.

$$Q_{95\%} = 10^{(avg(\log Q) - std(\log Q) \times 1.64)} \qquad (C.4)$$

Where
Q Discharge
avg Average function
std Standard deviation function

The spring at Barada has the monthly flow relationship determined with the rainfall in the catchment in the preceding three years. The same method and equation as is used for the annual spring flow determination is used. A set of equations is prepared, one per month for each period of time that there is no long tern trend in spring flow change.

At Figeh, work undertaken by Eng. Nibras El-Mouyad of DAWSSA is summarized in the section on Figeh Spring water quantity. Multiple regression equations with ten independent variables has been used to fit the observed flow data with other hydrological parameters. The equations have been used to predict the response of the spring to median and extreme conditions.

(4) Flow recession analysis

The analysis of the annual flow recession curves from springs and groundwater fed rivers permits the prediction of future discharge and the calculation of usable groundwater storage capacity in the aquifer. Reliable daily discharge measurements are required for the analysis. The flow recession is described by the general equation C.4. The volume of that part of the aquifer storage that can be used, known as active storage may be calculated (equation C.5) from a reformulation of equation C.4. The analysis was undertaken on the flow hydrographs for Barada and Figeh.

$$Q_t = Q_o\, e^{-wt} \qquad (C.5)$$

Where
$Q_t$ Discharge at time 't' in $m^3/s$
$Q_o$ Discharge at time zero in $m^3/s$
w Recession constant in per day
t Time in days
e Base of natural logarithms (approx. 2.7183)

$$S_t = \frac{Q_o\ e^{-\omega t}}{\omega} \qquad (C.6)$$

Where $S_t$ Storage in $m^3$
$Q_o$ Discharge at time zero in $m^3/d$

2.4.4 Spring Data Analysis Results

There is found to be a relationships between rainfall and annual spring flow for the majority of major springs in the Barada and Awaj catchment. Data from the 64 monitored springs for the period 1984/5 to 1995/5 are tabulated in Table C-2.9. From the full list of sites 9 have no or insufficient data, 16 do not have a identifiable relationship and the remaining 29 have their equations listed in Table C-2.10. Graphs of weighted rainfall against spring flow are reproduced in Data Book 4. The equations are used to calculate the spring flow anticipated at probabilities of rainfall exceeding 10% (wet year), 50% (average year), and, 95% (dry year). These can be compared with the calculated spring flows determined with data available up to 1985 and reported in Lengiprovodkhoz (1986). In all cases the more recent determinations are lower, for Figeh the difference is small, but most of the other springs have flows that are lower by 25% or more. For most of the springs there was seen to be a downwards trend in flows associated with changes to land use and abstraction in the spring catchment. This may be clearly observed in spring number 2 (Ain Hour), data for 1983 to 1989 lie upon one line, then there is a distinct break and the 1990 to 1994 flows are upon a line parallel and 20 l/s lower, most probably a consequence of a wellfield pumping within the spring catchment starting about 1990. The rainfalls are weighted in most cases with 70% from the current year, 20% from the previous year and 10% from the year before that. Springs with catchments that are more flashy do not have a carry over effect from the rainfall from previous years and so it has been found that the best relationship uses 100% of the rainfall from the current year.

The findings on long term trends, monthly spring flow and flow recession analysis are described for the principle springs of the study area in the next section.

2.4.5 Principal Springs in the Barada & Awaj Catchment

(1) Barada Spring

(a) Description

Barada spring is the perennial source of the river that bears the same name. It is located on the western side of the Zabadani Valley at the foot of Jabel Chir Mansour, about 30 km to the northwest of Damascus. The catchment area of the spring covers approximately 213 $km^2$ giving a long term natural recharge to the spring of 100 MCM/y, with an estimated groundwater storage of 6,000 MCM (Lengiprovodkhoz, 1986). The spring rises at an altitude of about 1090 masl, into the base of an artificial lake, 320 m long and about 70 m wide, the waters then flow over a penstock into the river channel, or may be directed via a lower level to an irrigation canal. The karst development is limited to the Jurassic Limestones in this area and so the spring has formed at the junction of the Upper Jurassic Limestone with overlying Lower Cretaceous strata. Graben faulting of Zabadani Valley has divided the Jurassic into many fault bounded blocks, possibly enhancing the bulk hydraulic properties in the vicinity of Barada Spring.

(b) Water quantity

The discharge of Barada has been measured from 1931 to 1993 at the gauging station Ramleh, 300 m down stream from the spring. A continuous hydrograph record for the period 1951 to 1984 is reproduced as annual graphs in Bashir (1987). Possibly due to the recorder mechanism the hydrograph appears step-like, small fluctuations in level at low discharge were not registered. Also, it may be seen clearly that the flow was influenced by artificial factors, for example from 1951 to 1975 there is always an increase in flow in the middle of May, while in 1979 & 1980 summer pumping has reduced the discharge. Measurements from this station have not been possible since 1993 due to changes to the channel. Work undertaken on behalf of the MOI to regard the upper reach of the Barada that would essentially lower to outflow point by 5 m was started but not completed. The contractor encountered rock in the base of the channel and has not completed the task. The net result being that the water level has submerged the gauged reach. The level in the lake or height in the channel has not been used as a substitute temporary measure. Presently flow is estimated from the gauging of the river 7 km downstream at Tekieh. This situation is not satisfactory since there are many factors that change the flow between Ramleh and Tekieh. Fortunately DAWSSA has the reconstruction of the gauging station on the river in the next 5 year plan.

(c) Stream hydrographs and recession analysis

A selection of annual stream hydrographs from Ramleh are illustrated in, Figure C-2.15. The spikes of high discharge over a short period of time in the winter period are due to storm runoff events. These high flows are superimposed upon a base flow derived from groundwater inflows. The base flow variation through the year is much smaller than that found at Figeh. A master recession curve for Barada, Figures C-2.16 and C-2.17, has typical recession constants of 0.00335 and 0.00154 $d^{-1}$, whereas the master recession curve at Figeh, Figure C-2.18, has larger recession constants. The baseflow storage below 4.5 $m^3/s$ amounts to a volume of 201 MCM which is larger than the volume of storage in Figeh when the discharge is 8 $m^3/s$. Most of the extra storage will only be evident in a very long and shallow recession below 3 $m^3/s$. The Barada hydrographs are influenced by the management of the spring by the MOI.

(d) Historical spring behavior

The long duration hydrography compiled from monthly flows illustrated in Figure C-2.19 shows what has happened to flows, but, it is difficult to identify any underlying trends from such a representation. However, the plot of cumulative rainfall against cumulative discharge from Barada Spring, Figure C-2.20, is much clearer, with two distinct sections. The period up to 1978 has a slope of 0.195 MCM/mm, which for a mean rainfall, is equivalent to a spring yield of 99 MCM/y. After 1978 there is a period of change, when there was a very significant reduction in reduction in spring flow, from 1983 to 1993 the slope is lower, 0.138 MCM/mm or a spring yield of 70 MCM/y. The reason for this reduction of 29 MCM/y is probably a combination of; a switch from using surface water for irrigation to the use of groundwater, the irrigation becoming more intensive irrigation exploiting groundwater that feeds the spring, an increase in municipal water abstraction to supply a larger demand from settlements in the Zabadani Valley. The current flow regime has not changed in the last 10 years, but, since the behavior of the spring shows that it is sensitive to activities in the Zabadani Valley, further changes should be anticipated. For example the exploitation of new groundwater wellfields to the north of the spring will further reduce the effective yield.

(e) Prediction spring discharge from rainfall

An investigation into the total spring flow and the minimum flow anticipated have been undertaken. The constants in the equation governing the relationship change from month to month, and are also different in the early flow regime (1961-76) and the more recent conditions (1982-93), Figures C-2.21 and C-2.22. The total discharge of the spring in the hydrologic year can be predicted from the mean rainfall in the catchment in the previous three years by a simple equation and set of constants, Table C-2.11 and Figure C-2.23. The equation may be used together with a knowledge of the precipitation characteristics to calculate the expected total discharge for various probabilities, Figure C-2.24. The table following gives the minimum expected flows for a year following two years with the median rainfall. The equation may be used to calculate the flow for any sequence of wet and dry years, Figures C-2.25 and C-2.26.

| Probability | Return Period | September ($m^3/s$) 1961-78 | September ($m^3/s$) 1982-93 | Total Flow (MCM) 1961-78 | Total Flow (MCM) 1982-93 |
|---|---|---|---|---|---|
| 50 | 1 in 2 | 2.29 | 1.87 | 97.8 | 70.8 |
| 75 | 1 in 4 | 2.02 | 1.71 | 80.7 | 64.4 |
| 90 | 1 in 10 | 1.75 | 1.55 | 63.7 | 58.4 |
| 95 | 1 in 20 | 1.64 | 1.48 | 57.0 | 55.7 |

(f) Field investigations and testing

The nature of Barada spring is a consequence of the hydrology and hydrogeology of the catchment area, as a consequence all the testing that has been done on groundwaters in the catchment shed light on Barada Spring. Five sets of tests have been undertaken; well pump tests on individual wells in neighboring wellfields, group pump test in the same wells from three wellfields 1.5 to 3 km north east of the spring, pump test of the pool, individual yield tests on Barada spring wellfield wells, and most recently, the operational use of the site is effectively a group test of the wellfield. A summary of the pertinent details of each of these tests is given in the following paragraphs.

Well Test Pumping. Ten wells were test pumped at different depth intervals by the MOI during the course of investigations from May 1983 to April 1985. The data and analysis are reported in Lengiprovodkhoz (1986). Transmissivities in the area are very variable ranging from 4 to 3085 $m^2/d$, with a median value of 1000 $m^2/d$ which is perhaps typical for the area as a whole, Table C-2.15.

Group Test Pumping of Wellfields in 1985-6. The test was undertaken by the MOI from mid November 1985 to mid March 1986. The results of are written up in Lengiprovodkhoz (1986). Three phases of pumping at progressively higher discharges from initially four wells at 220 l/s to six wells at 320 l/s to a final stage of eight wells with a combined output of 440 l/s. The pumping was done during the winter months when the effect of rainfall upon water levels makes the separation recharge and pumping effects difficult. The test was curtailed in March 1986 because the recharge made any interpretation of the pumping effects impossible. The early part of the test was less effected by rainfall and it was clearly seen that when pumping 220 l/s from wells which lie up hydraulic gradient from the spring reduces the spring flow by the same volume. The groundwater piezometry prior to the test, the iso-drawdowns and the spring discharge hydrograph illustrated in Figures C-2.27, C-2.28 and C-2.29 all testify to the direct relation between wellfield abstraction and spring flow reduction.

Pump Test of Barada Spring in 1987. A one hundred day test abstracting water directly from the spring pool was done by DAWSSA from September to December 1987. The data and analysis is reported in Bashir (1987). The level in the lake was lowered by almost 5 m and by a smaller amount in a set of nearby observation wells. The water pumped from the pool was discharged into the upper reach of the Barada River. The recession in spring discharge was determined prior to the commencement of the pumping, and it was assumed that this natural recession would have continued at the same rate had not the pumping taken place. The pumping achieved an average discharge of 2.54 $m^3/s$. The difference between the actual discharge and the assumed natural discharge was a total of 5.05 MCM, or an average of 609 l/s. Re-examination of the data in the course of the preparation of this master-plan document has drawn some further conclusions on the hydrogeological properties of the aquifer feeding the spring.

The piezometric map of the aquifer conditions prior to pumping, Figure C-2.27, depicts the flow convergence at the spring and in addition towards the upper reach of the Barada River. The iso-drawdown map, Figure C-2.28, shows a very lop sided cone of depression with drawdowns of over 3.5 m to the west of the spring while to the east the drawdown is less than 0.5 m in the vicinity of the river channel. This feature is probably due to a large permeability contrast across the site, or it is possible that there was some element of water recirculation during the test, water in the river channel infiltrating the aquifer and flowing back towards the pool. If the latter were the case then the estimate of the net increase of spring flow is too large.

The hydraulic properties of the aquifer feeding the spring may be determined from various water levels. To undertake these calculations the hydraulic system is assumed to be analogous to a large diameter well that is pumped at a variable rate to produce a fixed head for the natural recession period followed by a period of increased pumping to produce a variable head but a fixed discharge rate during the test period. In addition, since the system may be simplified to assume that the water flow only comes from the western side of the spring, it is analogous to a pumped site with an image well at the same location pumping at the same rate. Using these assumptions it is possible to obtain realistic and consistent results from the test data. For undertaking time-drawdown methods of analysis the change of pumping rate is used as effective the pumping rate, this is then doubled to account for the image well. Therefore a pumping rate of 1200 l/s is used for these analysis. For undertaking distance-drawdown methods of analysis the absolute pumping rate or discharge rate again multiplied by two is used. The piezometric surface prior to the test and the drawdowns are depicted on maps, Figure C-2.30 and C-2.31. The analysis graphs may be found in Figures C-2.32a to g, and a summary of the data and results in Table C-2.12. The results from the wells downstream from Barada such as P3 give un-representative hydraulic properties. In conclusion Barada spring has a zone of high transmissivity, about 17,000 $m^2/d$ around the source for a distance of about 4 km beyond which the transmissivity is about 2,000 $m^2/d$. Storage is 3% of aquifer volume, marginally higher than the storage in the Figeh catchment. These parameters may be used to predict the effect pumping in the vicinity of spring for DAWSSA's supply.

Yield Tests of Barada Wellfield. The 22 wells that comprise the Barada wellfield have each been tested. A simple yield drawdown test was used with 3 days of pumping at 56 l/s. The wells were tested progressively in the period October 1993 to April 1994. The specific yields are very variable in the range less than 0.1 to over 500 l/s/m with a median of 25 l/s/m, details may be found in Data Book 1.

(g) Operational use of Barada wellfield

The wellfield at Barada Spring was commissioned in the middle of 1995, and the full operational usage during the summer of 1996. A total of 22 production wells may be used which pump to an on-site reservoir, thence by gravity aqueduct to Figeh where it joins the tunnels to Damascus. The wellfield has a capacity of 1.1 $m^3/s$, and the aqueduct may transfer up to 3 $m^3/s$. The use of the water source has afforded DAWSSA the opportunity to conduct a test of the source, over a longer period than has yet been undertaken. Measurements of daily pumping and fortnightly levels in an observation well, plus the record of flows from Tekieh and Ramleh are available to study the effect of the pumping. The data is illustrated graphically for the period 1991 to 1996 and in greater detail February 1995 to August 1996, Figures C-2.33a and C-2.33b. The pumping started in July 1995 and increased in stages from 0.2 $m^3/s$ to almost 0.8 $m^3/s$ in January 1996. The wellfield was rested from February to May 1996 when abstraction restarted. The pumping rate has been further increased to a nearer normal operational volume of over 1 $m^3/s$. The effect of this pumping upon both water levels on the site and stream flow is not clear-cut. The water levels in the observation well drop rapidly by over 2 m before the pumping starts and a similar rise is recorded before the pumping stops. These changes may be attributable to changes in the lake level instigated by the MOI adjusting flows in its canals. On a theoretical basis and as has been seen in previous tests there is a decline in water level when the wellfield is pumped, however the effect is small and is masked by other events such as the natural water level recession and changes to the lake level. The flow at Tekieh gauging station was particularly low in 1995 and it has been recorded in the summer of 1996 to be less than 0.5 $m^3/s$. These low flows are almost certainly due to water abstraction between the spring and Tekieh, mainly from the DAWSSA wellfield, but also by local farmers for irrigation.

(2) Figeh Spring (Ain el Figeh)

(a) Description

Figeh is located 15 km to the northwest of Damascus. The springs have formed at the point where a south westerly plunging anticline of Cenomanian-Turonian limestones is cut by the Barada valley. The catchment area for the springs extends to the northeast of the springs consisting of the whole of the Cenomanian-Turonian outcrop with an area of 780 $km^2$. The source comprises three springs, namely Main Spring, Side Spring, Ain Haroush and 7 wells along the road to Deir Moukaren, Figure C-2.34.

In the Main Spring the flow rises up a single passage angled at about 45° to a depth of at least 100 m where a constriction in the passage limited the survey. The discharge from the Main Spring under natural conditions flowed into the Barada River, it has however been diverted into aqueducts to serve Damascus. In periods of low flow all the water is diverted, only the peak floods actually discharge to the river. The flow regime has been modified by a caisson which intersects the Main Spring channel at depth, this permits the pumping of the Main Spring at a rate greater than the natural discharge. Side Spring flow emerges from rock debris rather than from a clearly defined karstic passage. During the winter flood period the water flow Main Spring passes the Side Spring on the route to the spillway into the river. Whereas in the summer when all the flow is taken for supply there is no flow past Side Spring, and it has been also equipped with de-watering pumps to contribute to supply. The quantity abstracted is fixed to the natural inflow into Side Spring when the water level is depressed by 8.8 m, to the base of the pumps. Ain Haroush is separate from the two large springs at Figeh, in the base of the valley and about 500 m up stream. This spring only flows during the flood period being at a higher elevation than Main and Side Springs. It is also equipped with pumps that will de-water the spring to add to the Figeh source.

(b) Water quantity

The recharge is estimated at 219 MCM/y by this study, based upon the average conditions from 1957 to 1995. The recharge being about 55% of the precipitation in the catchment. The total storage within the karst aquifer system has been calculated from tritium concentrations, values of 5,400 MCM and 19,400 MCM have been reported by SOGREAH and Lengiprovodkhoz respectively. SOGREAH (1973 & 1975) used a quick mixing model in their analysis of the tritium data with the mean water exchange time (ratio of annual replenishment with storage) of 40 years. The storage estimate is considered by many workers to be an upper limit. The recharge for the spring has been reported at a higher figure of 243 MCM/y by Lengiprovodkhoz 1986, but this estimate uses spring flow data from 1932 to 1957 in the average flow calculation. The measurement of flow from Figeh was unreliable for this period when it was consistently over estimated. The average monthly flows of Figeh are produced in Data Book 3 for the period 1932 to 1995. The total discharge in millions of cubic meters (MCM) is calculated for both the calendar year (January to December) and the water year (October to September) for purposes of reference. Summary statistics for water quantity from Figeh are given in the following table. The mean is calculated from the logarithm of the monthly discharges to remove the positive skew of the data which would makes the arithmetic mean higher than the modal discharge. The 5% level at which there is 5% probability that it is exceeded, while the 95% level is the flow that there is a 95% chance of being exceeded, Figure C-2.35. These were calculated from the monthly standard deviation.

| Flow ($m^3/s$) | Jan | Feb. | Mar | Apr. | May | June | Jul. | Aug. | Sep | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 4.06 | 5.07 | 9.68 | 14.70 | 11.70 | 7.47 | 5.58 | 4.73 | 4.19 | 3.80 | 3.54 | 3.73 |
| 5% > | 7.28 | 8.79 | 17.32 | 24.44 | 25.52 | 16.42 | 10.57 | 8.16 | 6.98 | 6.33 | 5.75 | 6.29 |
| 95% > | 2.27 | 2.93 | 5.41 | 8.84 | 5.36 | 3.39 | 2.94 | 2.75 | 2.51 | 2.29 | 2.18 | 2.21 |

The hydrology of Figeh Spring catchment has not changed from 1961 to 1990. For this period a precipitation of 1 mm in the catchment has always yielded 0.445 MCM of discharge from the spring. The relationship is illustrated by the graph of cumulative rainfall against cumulative discharge volume being a straight line. The slight deviation from the straight line seen from 1990 to 1994 may not significant, but since it lies below the line it could mean that there are changes in land use and/or other abstractions in the Figeh catchment, Figure C-2.36.

Records of discharge date from 1942 for the Main Spring, from 1980 reliable records for the total flow from all springs are available. The annual hydrographs for the period up to 1968 are available in a report by SOGREAH (1971). Since 1988 hydrographs have been prepared and updated daily by DAWSSA. The graphical presentation on large sheets is compiled with the actual and mean cumulative rainfall, the chart is used for day to day assessment of the hydrology and used for production planning for the next few months. The annual hydrographs for 1992 to 1995 are illustrated in Figure C-2.37, the year 1992 being a very wet, while 1995 had near normal rainfall. The discharge rises soon after the first rainfall in October and then, in a series of stages builds up to a peak flow in March-April-May when the melting of winter precipitation augments the flow. There is no precipitation in the catchment during the summer when the hydrograph undergoes a long period recession. Modifications to the recession are caused by the pumping from the source, generally the recession continues with the same form during pumping but with the total flow increased by a consistent volume.

The discharge records and meteorological data has been intensely studied by both consultants and DAWSSA engineers. The primary purpose of the work is to establish a dependable method to enable the prediction of the discharge of the spring during the summer and flow recession. The study by SOGREAH adopted a descriptive method to characterize flow recession. Whereas the LaMoreaux (1982) work favored a model based upon physical processes that occur within the spring catchment area. A snow melt runoff model has been adapted for use on the Figeh catchment. The method requires a detailed information on the thickness and extent of snow and other meteorological data. DAWSSA has not been able to obtain the detailed data required for the model and consequently it has not been used. Currently

DAWSSA uses empirical approaches to forecast the total annual discharge of the spring; for example equation C.7 and the discharge during the recession; equation C.8.

$$Q_{total} = 327.5\,[\,R + 32\,Q_s\,] - 1893.62 \qquad \text{(C.7)}$$

Where
- $Q_{total}$ Total discharge volume in hydrological year in $m^3 \times 10^3$
- $R$ Rainfall averaged from 5 stations in mm
- $Q_s$ Discharge in September of previous year in $m^3/s$

$$Q = Q_o\, e^{ta} \qquad \text{(C.8)}$$

Where
- $Q$ Instantaneous discharge in $m^3/s$
- $Q_o$ Actual discharge at beginning of flow recession period in $m^3/s$
- $t$ Time elapsed since beginning of flow recession in days
- $a$ Empirical constant, unique to the year, typical value 0.006

The flow recession curve is divided by DAWSSA into up to four separate sections each with a different value for the flow recession constant, a. The individual flow recessions analyzed by DAWSSA are all part of the master flow recession for Figeh Spring. The combination of all the flow recessions since 1942 is illustrated in Figure C-2.18. All the recessions trend down to the master recession curve, a multitude of flow recession constants (a) exist, but the master recession has only three identifiable segments, Figure C-2.18. The master recession curve is used to calculated the storage remaining at any discharge. For example when the discharge of Figeh spring is 5.4 $m^3/s$ there is 109.8 MCM remaining in storage, more practically as the flow recedes to 3.3 $m^3/s$ in the following 155 days 52.8 MCM will be produced. The use of the master recession allows a quick method to determine the quantities available from natural spring flow.

An investigation into the total spring flow and the minimum flow anticipated have been undertaken using data provided with in the DAWSSA year book for 1994. The total discharge of the spring in the hydrological year can be predicted from the mean rainfall in the catchment in the previous three years by the simple relationship, Equation C.9 and Figure C-2.38. The equation may be used together with a knowledge of the precipitation characteristics to calculate the minimum expected total discharge for various probabilities, see the examples in the following table.

$$Q_{total} = 17.126\,(0.7\,R_n + 0.2\,R_{n-1} + 0.1\,R_{n-2}) + -1747 \qquad \text{(C.9)}$$

Where
- $Q_{total}$ Mean discharge in hydrological year in l/s
- $R$ Rainfall averaged from 5 stations in mm

| Probability (%) | Return Period | Minimum Total Flow (MCM) |
|---|---|---|
| 50 | 1 in 2 | 219 |
| 75 | 1 in 4 | 181 |
| 90 | 1 in 10 | 144 |
| 95 | 1 in 20 | 129 |

The relationship between rainfall in the year and the minimum flow that occurs in September, Figure C-2.39, shows the effect of antecedent conditions more strongly than the total flow relationship. A reduction in the data scatter is achieved by weighting the rainfall for a two year period. The table gives the minimum expected flows for a year following a year with the median rainfall. The equation may be used to calculate the flow for a sequence of wet and dry years.

$$Q_{Sept} = 850\,(0.75\,x\,R_1 + 0.25\,x\,R_2) - 75000 \qquad \text{(C.10)}$$

Where
- $Q_{Sept}$ Discharge in September in $m^3/d$
- $R_1$ Rainfall averaged from 5 stations for current year, in mm
- $R_2$ Rainfall averaged from 5 stations for previous year in mm

| Previous Year Probability (%) | Current Year Probability (%) | Minimum September Flow (l/s) |
|---|---|---|
| 50 | 50 | 4,400 |
| 50 | 75 | 3,590 |
| 50 | 90 | 2,660 |
| 50 | 95 | 2,430 |

A multivariate analysis of the fortnightly discharge is used for predicting flows and for planning the production program to be adopted by DAWSSA. The analysis was undertaken using the Microsoft Excel spreadsheet multiple logarithmic regression function on ten factors. The equation has the form below.

$$Q = c\; m_1^{x_1} m_2^{x_2} \ldots m_n^{x_n} \qquad \text{(C.11)}$$

Where
- Q Discharge
- c Constant
- $m_n$ Constant
- $x_n$ Parameters 1 to 10 as listed

1. Discharge on the preceding 15 September, in cubic meters per second.
2. Discharge on the 15 September 2 years ago, in cubic meters per second.
3. Precipitation in the Figeh Catchment as measured by the DAWSSA meteorological network in the preceding hydrological year in millimeters.
4. Precipitation in the Figeh Catchment as measured by the DAWSSA meteorological network in the hydrological year two years ago, in millimeters.
5. Precipitation in the Figeh Catchment as measured by the DAWSSA

meteorological network in the current hydrological year in millimeters.

6. Main Floods, the number of half months since the beginning of January until the time of the peak discharge. Accounts for the date of the late snow melt
7. Early Floods, a summation of the difference between the minimum flow in the previous hydrological year and the actual flow for each half month period from the minimum flow until the beginning of March, units summed in cubic meters per second.
8. Peak Discharge, the maximum flood flow recorded for the current hydrologic year in cubic meters per second.
9. Pumping, the number of half months when the springs were pumped in the previous year.
10. Pumping, the number of half months when the springs were pumped two years ago.

A regression analysis was done for the beginning and middle of each month from April to February and a different set of multiple regression constants are obtained. The analysis was undertaken using 17 years of data (1979/80 to 1995/96) and achieves high regression correlation coefficients. The equation factors and two examples of using the equations to predict flows are found in Table C-2.13, and the results compared with actual flows in Figure C-2.40. The equations will work well to predict the flows during the calibrated period, which, considering the large number of 'independent' variables is not unexpected. However without examining the components that result in the final flow prediction one can not see which of the factors are important since the constants are all very close to unity. The calculation of the $m^x$ components of the final flow is useful in this respect. Components where this term is still near to unity are poor explanatory factors in the total flow prediction. It can be seen from Table C-2.13 that the early flood factor, and the two pumping factors have very little predictive power in any of the equations, whereas precipitation and September flows have components that are significantly different to unity. It should be expected that the components have a systematic change from one half month period to the next. However, certain components fluctuate apparently randomly, for example the peak flow factor for September to October wobbles from 0.62 to 0.36 to 0.74. Within the regression equation other factors compensate and the equations will fit for explaining the data set from which they were derived; however, future calculated flows may have wild and unreasonable predictions especially if the initial conditions are not near to those used for the determination of the equations in the first place.

(c) Aquifer properties

Pumping tests were conducted on the springs in 1981 and 1982 with observation wells in the area used to determine the cone of depression, see Gilbert and LaMoreaux (1982). The hydraulic properties from the tests indicate a very high transmissivity ranging from 6,000 to 75,000 $m^2$/d from Ain Haroush, 4,500 to 450,000 $m^2$/d from the Side Spring, and 63,000 to 852,000 $m^2$/d from the Main Spring. The wide variation in the transmissivity is typical of a methods are not met.

(d) Operational behavior

Daily records of the flow, level and temperature are held on the DAWSSA main computer. The period from 1985 to 1991 is partially documented, while the last four years have a comprehensive data set. A summary diagram, Figure C-2.41, shows the manner in which the source is used: During the flood water is taken by gravity flow, while the surplus overflows into the Barada River. As flows decline the amount of over flow is reduced until all the gravity flow is used for supply. Pumping commences from the springs once gravity flows are insufficient, these then continue until recharge of the springs rise the natural discharge rate. A detailed graph for each year, Figure C-2.42, shows the source of the pumped water. Most of which is abstracted from Main Spring, from 3 to almost 6 $m^3/s$, the Side Spring component is about 1 $m^3/s$ and up to 0.5 $m^3/s$ originates from Ain Haroush. The pumped quantities from Side and Ain Haroush are consistent through the pumping period, the decline in total output is due to the variable amount that may be taken from Main Spring. The water levels in Side Spring have been at either 825 masl when the spring overflows or at 816 masl when it is pumped, the decline in level is rapid when the pumping starts, see Figure C-2.43. The water level in Main Spring is between 826 and 827 masl during overflow times, and the pumped level between 820 and 821 masl, Figure C-2.44. Ain Haroush has been the smallest of the springs, the source overflowing once levels are over 828 masl. Pumping causes a pattern of water level decline that does not differ much from year to year, Figures C-2.45 and C-2.46. With the present pumping equipment the water levels are lowered to about 818 masl in 100 days. The drawdown is equivalent to about 20 $m/m^3/s$, excluding any correction for the natural background fall in water levels.

2.4.6 Minor Springs of the Barada and Awaj Catchment

(1) Springs of the Zabadani Valley

The majority springs in the Zabadani valley issue at the geological boundary of the Jurassic or Cretaceous limestone. There are 12 springs to the north east of Barada for which monthly flow records exist, only three have produced flows greater than 100 l/s in the last ten years; Sarada, Ain el Irk and Nabua. The current spring behavior has been characterized by the response to rainfall and the reduction of flow by artificial effects. The flow is reduced in all of the springs, a very clear example of this is illustrated by the behavior of Ain Hour (No 2). Data for the period 1984 to 1989 lies on one line, after this time a wellfield with a capacity of 17 l/s was constructed in the catchment of the spring, the average yield dropped almost the same amount (20 l/s), from 32 l/s to 12 l/s.

Five of the springs are fed from the Jurassic of the eastern side of the Zabadani Valley; Sarada, Ain Hour, El Irk, Abu Zad and Ain Beda. The natural discharge from the aquifer via the recorded springs is 9.27 MCM (Lengiprovodkhoz), the current discharge is 6.81 MCM, a loss of 2.46 MCM (80 l/s), a volume that can be almost completely explained by the groundwater abstraction. The recharge area may be calculated, assuming the same effective recharge rate as in the Figeh catchment (280 mm/y), an area of 33 $km^2$ is required to support the spring flow. This area is slightly larger than the area of Jurassic outcrop which is only 25 $km^2$, the implication is that either the catchment includes some of the ajoining Cretaceous rocks, or, more likely, that the higher rainfall results in an average recharge of 370 mm/y.

(2) Springs of the Awaj Valley

The two headwater streams that form the Awaj are both fed by many springs from the Jurassic limestone of Jabel esh Sheikh. Upon the Janani River four main springs rise; Ras el Nabei, Beit Jenn, Membej and Talmasieh. They are considered a promising water resource and their hydrology is described in the section on new resources. The Sebrani River has six monitored springs, their flows are all significantly less than those from the Janani Valley. There is only one large spring on the Awaj River, Tabibiyeh, this is described in the section on new resources. The Sebrani River is fed by many springs in the Rimeh and Arneh area rising at a higher elevation than those in the Janani valley. The total recharge to Jabel esh Sheikh is about 320 MCM. The recharge supplies the springs on the eastern flanks with a about 26 MCM/y, while on the western flanks about 31 MCM/y. However, since the principal flow is to the south east most of the flow emerges at just two springs; Dan and Banias, the flow from these two amounting to 360 MCM/y.

## 2.5 Hydrogeology

### 2.5.1 Main Aquifers

(1) Upper Quaternary to Recent alluvial-proluvial aquifer

(a) Nature and occurrence

The aquifer occurs in the El Arab Trough, specifically in the Damascus and Dmeir alluvial fans and along the Awaj River, see the hydrogeological map Figure C-2.47. The sediments consist of principally pebble beds, weakly cemented conglomerates with sand and clay lenses. The upper portion is more argillaceous, where the clay and loam may be up to 20 m thick. The unit is roughly wedge shaped, adjacent to the Kassioun Mountain has been

20 m thick. The unit is roughly wedge shaped, adjacent to the Kassioun Mountain has been recorded as up to 93 m thick, to the south and east it quickly thins and finally wedges out completely. The individual pebble beds are thin and often are not individually distinguished in the wells drilled in the city. The total thickness of these pebble beds have been mapped by detailed investigations, the pebble beds are over 40 m thick in places and underlie the current course of the Barada. Under Damascus the alluvial-proluvial strata overlies older Quaternary lacustrine-alluvial sediments, while south of Damascus they overlie Pliocene conglomerate and Miocene basalt.

(b) Groundwater flow

Groundwater occurs at a shallow depth either confined or semi confined by the clay horizons in the Quaternary. In the north west part of the city and at the foot of Kassioun, (near to the limit of saturation) the depth to groundwater is about 30 m. Moving south east across the area the depth to water declines to 0.5 m. To the east of Damascus there are some springs fed by the this groundwater. A piezometric map of the groundwater for the whole of the Quaternary aquifer for September 1995 has been prepared with information from the MOI, Figure C-2.48. The groundwater flow pattern has not changed in the last 10 years, although the absolute levels have declined. The flow is directed towards the plains east of the Damascus Ghouta, generally to the south east and roughly coincides with the surface topography. The discharge zone for the groundwater under natural conditions was to the internal drainage basins, though springs at the perimeter of the alluvial fan and groundwater flow to the lakes. The water lost to the basin by evaporation from surface water bodies and shallow groundwater in sabkah conditions. Within the city the influence upon the piezometric surface of the DAWSSA production wells is considerable. For example the levels in 1994 in June before pumping start follow the regional pattern, after 5 months pumping the cones of depression from the wells have merged to give a regional depression of water levels, Figures C-2.49, 50, and 51.

(c) Groundwater level fluctuation

Currently the water levels in Quaternary as a whole are declining. This is since the volume of groundwater that reaches the area is much diminished compared with the past and there are many artificial abstractions in the area. The picture is not the same over the whole area, levels have declined in the shallow aquifer east of Damascus, for example a monitoring well at Kafrain, (30 km east of the city) Figure C-2.52, has declined by about 20 m in a six year period 1986 to 1992. Meanwhile water levels near the city, Well 191, do not show any clear long term trend, Figure C-2.53. Water levels from DAWSSA observation wells can only act as a guide since they are mainly effected by the pumping each year, Figure C-2.54. All the hydrographs for DAWSSA observations wells are produced in Data Book 5.

(d) Hydraulic properties

The hydraulic properties of the sediments are variable, tests analyzed by the Soviet team report a mean permeability and transmissivity of 0.066 cm/s (57 m/d) and 1325 $m^2/d$ respectively, Table C-2.14. A band of high transmissivity runs down the alluvial fan downstream from Damascus, along the location of the thickest pebble beds. The distribution of The aquifer can be highly productive with yields in excess of 30 l/s (108 $m^3/h$) achieved by many wells. The wells in the DAWSSA wellfields are pump tested following construction, the specific capacity is highly variable, Figure C-2.55, the specific capacity of 90 % of wells is greater the 0.8 l/s/m while 10 % have specific capacity greater then 10 l/s/m. The spatial distribution of specific capacity within the DAWSSA well tests does not indicate any pattern, for example at Kywan adjacent holes vary between 12.6 and 0.1 l/s/m. Summary details of the pump tests may be found in the well inventory, Data Book 1.

(e) Recharge

The aquifer is mainly recharged by surface water infiltration from the Barada and its distributor channels. Isotopic studies have demonstrated that the waters under Damascus urban area are recharged by the Barada and city waste water, whereas outside the city limits the only source identified in the groundwater was the Barada River. The leakage of the water distribution system, and to a lesser extent from the waste water system, no doubt plays a role in recharging the aquifer. Water may also recharge the aquifer from the Cenomanian-Turonian limestones, either by upward leakage through the underlying Quaternary lacustrine sediments and also directly at the junction along the Damascus fault. Quantification of the various components is particularly difficult, and in the absence detailed data only a rough estimate may be attempted.

(f) Water resources determination

The water resources are calculated to be 406 MCM/y (an average of 12.9 $m^3/s$) by work in the 1980's (Lengiprovodkhoz 1986). This value represents the water resources for the alluvial and proluvial aquifer, area being defined as the limits of the saturated aquifer where the transmissivity is greater than 100 $m^2/d$. The area lies along the course of the Barada River downstream from Rabouyeh and approximately the extent of the Upper Quaternary pebble beds. Within this zone the water resources were assessed by a water balance method. The equation for natural conditions balances the water inputs with the outputs.

$$Q_1 + Q_2 + Q_3 = Q_4 + Q_5 + Q_6 \qquad (C.12)$$

Where
- $Q_1$ Seepage losses of the Barada River surface water
- $Q_2$ Groundwater inflow into the area from Kassioun Mountain
- $Q_3$ Recharge from infiltration of rainfall
- $Q_4$ Evaporation from groundwater surface
- $Q_5$ Spring flow
- $Q_6$ Groundwater flow out of the area towards Lake Ateibeh Lake

The present water balance equation must however be adjusted to account for the modifications to the hydrological cycle by human activities. The construction of irrigation canals, water supply and sewerage systems and use of wells to abstract groundwater are accommodated in the revised water balance equation, C-2.12. The $Q_1$ term is replaced by four additional terms $Q_{11,12,13,14}$ each which have a coefficient of alpha (a). The replacement terms represent; seepage losses from the unregulated Barada River, leakage losses from the DAWSSA water supply system and the sewage system, seepage from irrigation canals and the use of river water for irrigation, and seepage from groundwater used in water supply or irrigation.

$$\alpha_1 Q_{11} + \alpha_2 Q_{12} + \alpha_3 Q_{13} + \alpha_4 Q_{14} + Q_2 + Q_3 = Q_4 + Q_5 + Q_6 \qquad (C.13)$$

Where
- $Q_{11}$ Unregulated discharge of the Barada River
- $Q_{12}$ Water abstracted from Figeh Spring and used for public supply
- $Q_{13}$ Surface water discharge into irrigation channels
- $Q_{14}$ Groundwater abstraction from wells and wells
- $\alpha_{1,2,3,4}$ Recharge coefficients

It is argued that once groundwater resources are fully utilized that there will be no outflows from the balance area, $Q_4$, $Q_5$ and $Q_6$ will be zero. Also the recharge coefficients in principle are different for each component and are likely to vary spatially and temporary, nonetheless for estimation purposes a mean value of alpha is employed. The total groundwater resources may be determined by a rearrangement of the previous equation to give equation C.13.

$$R = \frac{\alpha}{1-\alpha}(Q_{11} + Q_{12} + Q_{13}) + \frac{1}{1-\alpha}(Q_2 + Q_3) \qquad (C.14)$$

Where
- R Water resources
- $\alpha$ Mean recharge coefficient, determined from mathematical modal as 0.42

Substituting into the equation values for mean parameters allow the total water resources to be calculated. For the period 1979/80 to 1983/84 hydrological measurements of river flows and water supplied from Figeh were used in the equation. Groundwater inflows were taken from a mathematical model of the aquifer as an unchanging 49.7 MCM/y and recharge to the area taken as 34.3 mm/y over a 500 km$^2$ area. Using these number the recharge was calculated to be 406 MCM/y. For the period 1990/91 to 1993/94 the discharge of the Barada River as it enters the Damascus depression is lower, the mean value at El Hame being 188 MCM/y, during the same period the production from Figeh was a mean of 157 MCM/y. These more recent hydrological data reflect both the increase in use of Figeh as a public water supply and a reduction in the flow of the Barada due to more irrigation activities in the Barada catchment upstream of Damascus. The latter data when used in the equation C.13 results in a revised water resources estimate of 365 MCM/y (11.6 m$^3$/s). The various abstractions from the aquifer under the same time period are not known in total however DAWSSA's abstractions are currently 35 MCM/y from the aquifer, the rural water establishment abstracts about 37 MCM/y from around Damascus and irrigation use was 292.8 MCM/y (figure from the early 1980's), a total of 365 MCM/y, coincidentally numerically equivalent to the water resources. In the upper Quaternary aquifer as a whole the balance between abstraction and replenishment is very near to the maximum utilization. The fact that there does not appear to have been a systematic decline in water levels in the part of the aquifer under the city does not necessarily imply that the methodology is fundamentally flawed. There may be estimation errors in the recharge coefficient resulting in a greater recharge that calculated or there may be portions of the aquifer further to the east where there is a local net deficit. The decline in water levels in wells to the east of the city seem to substantiate this suggestion.

The water balance assessment of water resources may be carried out on smaller units than the aquifer as a whole, although more assumptions have to be made to qualify the technique. The instrumentation of surface and groundwaters in the immediate vicinity of the city is not sufficient to reliably carry out a water balance on the zone with both high well yields and good water quality.

The water resources reflect the total replenishable groundwater, they do not imply that all the water resources may be useable for public water supply. The portion of useable aquifer are dictated by physical and chemical constraints. Firstly the aquifer should have hydraulic characteristics that permit the construction of wells with an acceptable yield and secondly the water quality should be such that the water may be easily treated, blended if necessary before addition to the distribution system.

(2) Cenomanian-Turonian limestone aquifer

(a) Nature and occurrence

The Cenomanian-Turonian strata occurs over almost all of the Damascus Basin. It outcrops on the flanks of the Anti Lebanon Mountains, while younger deposits cover the strata in the intermontane basins and the Al-Arab trough. The thickness ranges from 400 m in the Ad-Dmeir mountains to 1000 m in Jabel esh Sheikh. The rocks are predominantly massive and thick bedded dolomite and limestone with rare localized interbeds of marl and sandstone. The rocks are folded and faulted with zones of very high fissuring occurring in the anticlines. Development of karstic fissures is extensive throughout the whole thickness of the rock within the anticlinally formed mountains. In the Al-Arab Trough the rocks are at great depth, over 1 km below the surface, and the fissuring is much less intensive.

(b) Groundwater flow

Groundwater movement is generally to the east and south east towards the El-Arab trough, Figure C-2.48. The preferential movement of groundwater along the axial zones of major anticlines is observed within the Figeh mountain block where the flow is to the south west fixed by the fold structure and the overlying Palaeogene aquiclude. The groundwater issues at major springs and discharges into the Barada River. Over much of the area the Cretaceous limestone is in hydraulic continuity with the underlying Jurassic aquifer. Where faulting has brought the Jurassic and Cretaceous together there can be poor lateral connection. This is seen east of Deir al Ashayer where there is a steep hydraulic gradient between two blocks of Cretaceous caused by the faulting on the perimeter of Jabel Mansoor.

(c) Groundwater level fluctuations

Seasonal changes in water level are large in the upper parts of the groundwater catchments. For example well 809b near Deir al Ashayer has a typical natural water level change of about 10 m, Figure C-2.56. Long term changes in water levels have not been seen in the limestone aquifer.

(d) Hydraulic properties

Hydraulic properties of the rock en-mass are highly variable. The yields from wells can, range virtually dry to 110 l/s/m over a few hundred meters. The transmissivity can exceed 10,000 $m^2/d$ while in a significant proportion of wells the transmissivity is less than 100 $m^2/d$. The variability of the aquifer is shown in the distribution of well specific capacities for DAWSSA wells, Figure C-2.57, 90% of wells have a Q/s of greater than 2 l/s/m and 10% have a Q/s of greater than 200 l/s/m.

(3) Jurassic aquifer

The Jurassic strata occurs throughout the area, for the most part overlain by younger deposits, with outcrops on Jabel Mansour, Jabel esh Sheikh and Jabel Ash Shakif. The formations are mainly limestone and dolomite with interlayers of marls having a total thickness of up to 1,500 m. The groundwater movement is by fissure flow and consequently the bulk hydraulic properties are highly variable. The specific capacities from wells at Barada tested by DAWSSA, transmissivities and permeabilities that exist, can be seen by reference to Table C-2.15.

2.5.2 Minor aquifers

Minor aquifers which may be local importance for local water supplies or have poor hydraulic properties include; Quaternary to Recent lacustrine deposits, basalts of middle Miocene/Pliocene to lower Quaternary age, Upper Eocene-Oligocene deposits, Lower Cretaceous (Albian & Aptian Aquifers).