REPUBLIC OF YEMEN
MINISTRY OF WATER AND ENVIRONMENT
SANA'A BASIN WATER MANAGEMENT PROJECT

(IDA CREDIT 3774-YEM)

Sub-Component 3(d)

Hydro-geological and Water Resources Monitoring and Investigations

ACTIVITY 4: HYDROLOGICAL MONITORING AND ANALYSES IN SANA'A BASIN

DRAFT FINAL REPORT
(Part I: Rainfall and Meteorological Network)b

by
Dr. Khaled Kheireldin
Regional Consultant

Financed by: The World Bank

April, 2009

HYDROSULT Inc.
Consultants, Experts-conseils

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The literature review revealed that about 24 rainfall stations have been installed in the area of Sana'a Basin since 1970. Of these stations, 15 were installed at different locations within the basin area while 9 others were installed outside Sana'a Basin boundary at a close distance from the basin's boundary. These stations were installed through the support of different projects over the 36-year time period. Review of the reliability of these stations showed that none of them has continuous records for the whole of the 36 years. Some of these stations recorded rainfall over a two-year period, others recorded for five-year period and, in most of the stations, the longest recording period was seven years. In addition, the review showed that the longest recorded period from a single station was 22 years, at Al-Salf station. On the other hand, Sana'a Basin is located in a semi-arid zone having a very complex topography with a significant variation in the rainfall intensity and rainy days. In the north-eastern part of the basin, the rain intensity reaches 170 mm/year while, in the south-western part, it reaches 330 mm/year. In addition, the nature of the spatial distribution of rainfall over the basin varies drastically from one location to another. Thus, the need for a robust rainfall monitoring network for the entire basin, which has an area of f 3200 km^2, is indispensable to generate reliable information on rainfall and weather in the Sana'a Basin.

Field visits to inspect all of the existing rainfall monitoring stations in the basin were conducted. During these field visits the stations' status and operation processes were evaluated. All rainfall stations are installed on the roofs of governmental buildings; however, two climatic stations are installed in open areas. Normally, rainfall stations are installed in open areas rather than within closed areas, at distances of 2-5 km from high mountains or tall buildings... This assures that rain-shadow effect is minimized and that the station presents the real situation. The data collection procedure was also evaluated, and it was concluded that the system is capable of controlling the data collection time intervals from monthly data points to one-minute time steps. Data was collected and analyzed to develop a storm pattern for Sana'a Basin. Preliminary data analysis showed that the data collection system should be re-adjusted to 5-minute time steps since the type of storm resembles the semi-arid-type storms that require smaller time step to typify them. Accordingly, it was decided to re-adjust the time step to 5 minutes at all stations. Starting from the upcoming rain season, which starts in March 2007, rainfall data will be collected on a 5-minutes time step basis. However, the total number of existing rainfall stations is eight, while the total number of meteorological stations was only two.

Any method of measuring precipitation should aim to obtain a sample that is representative of the true amount falling over the area, which the measurement is intended to represent, whether on the synoptic, meso- or micro- scale. The choice of site, as well as the systematic measurement of errors is, therefore, important. To determine the new rainfall and meteorological stations' locations, preliminary rainfall analysis was performed on the available data from 1972 to 2005. Different analyses were performed such as variogram analysis, krigging analysis and residual-error analysis. From the statistical analysis, it can be concluded that the total number of rainfall stations within the entire basin should be in the range of 30 to 44 rainfall stations.

The following selection criteria are considered for the new stations:

- draw lessons from the residual errors in the existing rainfall station analyses;
- consider the location of the existing meteorological and rainfall stations;
- the elevations of the new stations should be extended to the highest and lowest elevations within the basin, thus the relationship between the ground elevation and rainfall intensity can be developed;
- distribution of the stations in the different sub-basins.

Field visits to the proposed locations were performed to assign the final location for the new stations. Finally, 35 new rainfall stations and 8 meteorological stations are proposed to present the new designed monitoring network within Sana'a Basin.

Chapter 1. WORLD METEOROLOGICAL ORGANIZATIONS STANDARDS FOR DESIGN OF WEATHER AND PRECIPITATION NETWORKS

1.1 Introduction

This chapter describes the well-known methods of precipitation measurement at ground stations based on World Meteorological Organizations (WMO) Standards. This chapter was prepared with the purpose of serving as a Guide for rainfall Measurement and Processing. The chapter does not discuss measurements which attempt to define the structure and character of precipitation, or which require specialized instrumentation, which are not standard meteorological observations (such as drop size distribution). The general problem of rainfall representation is particularly acute in the measurement of precipitation. Precipitation measurements are particularly sensitive to exposure, wind, and topography and metadata describing the circumstances of the measurements are particularly important for users of the data. Analysis of precipitation data is much easier and more reliable if the same gauges and siting criteria are used throughout the networks. This should be a major consideration in designing networks.

1.1.1 Precipitation Definition

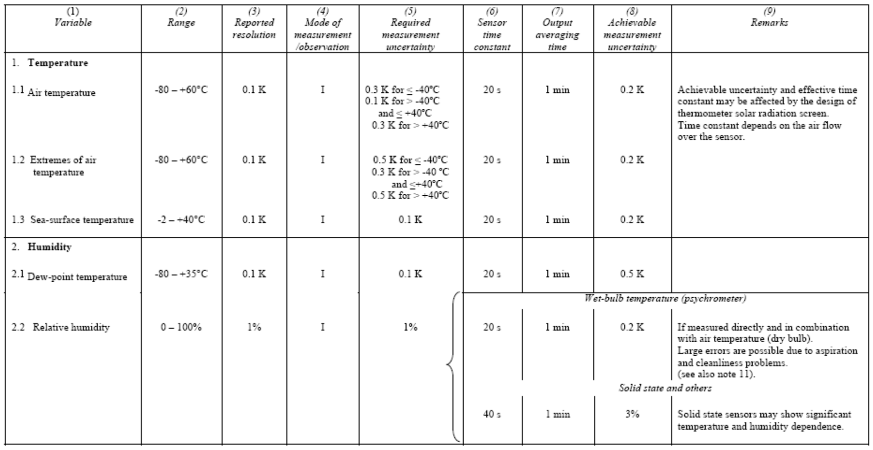
Precipitation is defined as the liquid or solid products of the condensation of water vapor falling from clouds or deposited from air on the ground. It includes rain, hail, snow, dew, rime, hoar frost and fog precipitation. The total amount of precipitation which reaches the ground in a stated period is expressed in terms of the vertical depth of water (or water equivalent in the case of solid forms) to which it would cover a horizontal projection of the Earth’s surface.

1.1.2 Units and Scales

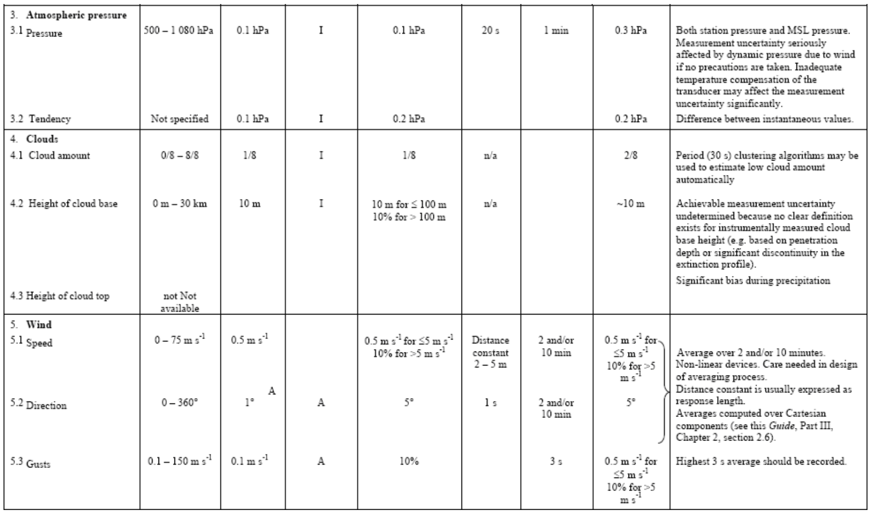
The unit of precipitation is linear depth, usually in millimeters (volume/area), or kg m-2 (mass/area) for liquid precipitation. Daily amounts of precipitation should be read to the nearest 0.2 mm and, if feasible, to the nearest 0.1 mm; weekly or monthly amounts should be read to the nearest 1 mm (at least). Daily measurements of precipitation should be made at fixed times common to the entire network or networks of interest. Less than 0.1 mm (0.2 mm in the United States) is generally referred to as a trace. The rate of rainfall (intensity) is similarly expressed in linear measures per unit of time, usually millimeters per hour.

1.1.3 Meteorological and Hydrological Requirements

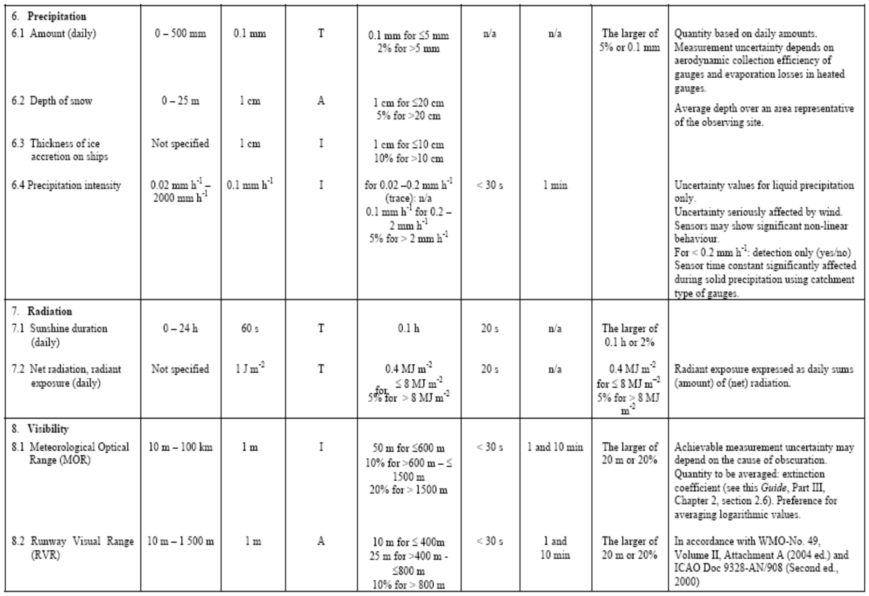
Table 1, gives a broad statement of the requirements for accuracy, range and resolution for precipitation measurements and gives 5 percent as the achievable accuracy (at the 95 percent confidence level). The common observation times are hourly, three-hourly and daily, for synoptic, climatological and hydrological purposes. For some purposes, a much greater time resolution is required to measure very high rainfall rates over very short periods. For some applications, storage gauges are used with observation intervals of weeks or months or even a year in the mountains and deserts.



(1) Variable	(2) Range	(3) Reported resolution	(4) Mode of measurement /observation	(5) Required measurement uncertainty	(6) Sensor time constant	(7) Output averaging time	(8) Achievable measurement uncertainty	(9) Remarks
1. **Temperature**								
1.1 Air temperature	-80 – +60°C	0.1 K	I	0.3 K for ≤ -40°C 0.1 K for > -40°C and ≤ +40°C 0.3 K for > +40°C	20 s	1 min	0.2 K	Achievable uncertainty and effective time constant may be affected by the design of thermometer solar radiation screen. Time constant depends on the air flow over the sensor.
1.2 Extremes of air temperature	-80 – +60°C	0.1 K	I	0.5 K for ≤ -40°C 0.3 K for > -40 °C and ≤+40°C 0.5 K for > +40°C	20 s	1 min	0.2 K	
1.3 Sea-surface temperature	-2 – +40°C	0.1 K	I	0.1 K	20 s	1 min	0.2 K	
2. **Humidity**								
2.1 Dew-point temperature	-80 – +35°C	0.1 K	I	0.1 K	20 s	1 min	0.5 K	
					Wet-bulb temperature (psychrometer)			
2.2 Relative humidity	0 – 100%	1%	I	1%	20 s	1 min	0.2 K	If measured directly and in combination with air temperature (dry bulb). Large errors are possible due to aspiration and cleanliness problems. (see also note 11).
					Solid state and others			
					40 s	1 min	3%	Solid state sensors may show significant temperature and humidity dependence.



(1) Variable	(2) Range	(3) Reported resolution	(4) Mode of measurement /observation	(5) Required measurement uncertainty	(6) Sensor time constant	(7) Output averaging time	(8) Achievable measurement uncertainty	(9) Remarks
3. **Atmospheric pressure**								
3.1 Pressure	500 – 1 080 hPa	0.1 hPa	I	0.1 hPa	20 s	1 min	0.3 hPa	Both station pressure and MSL pressure. Measurement uncertainty seriously affected by dynamic pressure due to wind if no precautions are taken. Inadequate temperature compensation of the transducer may affect the measurement uncertainty significantly.
3.2 Tendency	Not specified	0.1 hPa	I	0.2 hPa			0.2 hPa	Difference between instantaneous values.
4. **Clouds**								
4.1 Cloud amount	0/8 – 8/8	1/8	I	1/8	n/a		2/8	Period (30 s) clustering algorithms may be used to estimate low cloud amount automatically
4.2 Height of cloud base	0 m – 30 km	10 m	I	10 m for ≤ 100 m 10% for > 100 m	n/a		~10 m	Achievable measurement uncertainty undetermined because no clear definition exists for instrumentally measured cloud base height (e.g. based on penetration depth or significant discontinuity in the extinction profile). Significant bias during precipitation
4.3 Height of cloud top	not Not available							
5. **Wind**								
5.1 Speed	0 – 75 m s^{-1}	0.5 m s^{-1}		0.5 m s^{-1} for ≤5 m s^{-1} 10% for >5 m s^{-1}	Distance constant 2 – 5 m	2 and/or 10 min	0.5 m s^{-1} for ≤5 m s^{-1} 10% for >5 m s^{-1}	Average over 2 and/or 10 minutes. Non-linear devices. Care needed in design of averaging process. Distance constant is usually expressed as response length. Averages computed over Cartesian components (see this *Guide*, Part III, Chapter 2, section 2.6).
5.2 Direction	0 – 360°	A 1°	A	5°	1 s	2 and/or 10 min	5°	
5.3 Gusts	0.1 – 150 m s^{-1}	0.1 m s^{-1}	A	10%		3 s	0.5 m s^{-1} for ≤5 m s^{-1} 10% for >5 m s^{-1}	Highest 3 s average should be recorded.



(1) Variable	(2) Range	(3) Reported resolution	(4) Mode of measurement /observation	(5) Required measurement uncertainty	(6) Sensor time constant	(7) Output averaging time	(8) Achievable measurement uncertainty	(9) Remarks
6. **Precipitation**								
6.1 Amount (daily)	0 – 500 mm	0.1 mm	T	0.1 mm for ≤5 mm 2% for >5 mm	n/a	n/a	The larger of 5% or 0.1 mm	Quantity based on daily amounts. Measurement uncertainty depends on aerodynamic collection efficiency of gauges and evaporation losses in heated gauges.
6.2 Depth of snow	0 – 25 m	1 cm	A	1 cm for ≤20 cm 5% for >20 cm				Average depth over an area representative of the observing site.
6.3 Thickness of ice accretion on ships	Not specified	1 cm	I	1 cm for ≤10 cm 10% for >10 cm				
6.4 Precipitation intensity	0.02 mm h^{-1} – 2000 mm h^{-1}	0.1 mm h^{-1}	I	for 0.02 –0.2 mm h^{-1} (trace): n/a 0.1 mm h^{-1} for 0.2 – 2 mm h^{-1} 5% for > 2 mm h^{-1}	< 30 s	1 min		Uncertainty values for liquid precipitation only. Uncertainty seriously affected by wind. Sensors may show significant non-linear behaviour. For < 0.2 mm h^{-1}: detection only (yes/no) Sensor time constant significantly affected during solid precipitation using catchment type of gauges.
7. **Radiation**								
7.1 Sunshine duration (daily)	0 – 24 h	60 s	T	0.1 h	20 s	n/a	The larger of 0.1 h or 2%	
7.2 Net radiation, radiant exposure (daily)	Not specified	1 J m^{-2}	T	0.4 MJ m^{-2} for ≤ 8 MJ m^{-2} 5% for > 8 MJ m^{-2}	20 s	n/a	0.4 MJ m^{-2} for ≤ 8 MJ m^{-2} 5% for > 8 MJ m^{-2}	Radiant exposure expressed as daily sums (amount) of (net) radiation.
8. **Visibility**								
8.1 Meteorological Optical Range (MOR)	10 m – 100 km	1 m	I	50 m for ≤600 m 10% for >600 m – ≤ 1500 m 20% for > 1500 m	< 30 s	1 and 10 min	The larger of 20 m or 20%	Achievable measurement uncertainty may depend on the cause of obscuration. Quantity to be averaged: extinction coefficient (see this *Guide*, Part III, Chapter 2, section 2.6). Preference for averaging logarithmic values.
8.2 Runway Visual Range (RVR)	10 m – 1 500 m	1 m	A	10 m for ≤ 400m 25 m for >400 m - ≤800 m 10% for > 800 m	< 30 s	1 and 10 min	The larger of 20 m or 20%	In accordance with WMO-No. 49, Volume II, Attachment A (2004 ed.) and ICAO Doc 9328-AN/908 (Second ed., 2000)

Table 1-1 Operational measurement uncertainty requirements and instrument performance

1.2 Method of Measurements

Precipitation gauges (or rain gauges if only liquid precipitation can be measured) are the most common instruments used to measure precipitation. Generally, an open receptacle with vertical sides is used, usually in the form of a right cylinder, and with a funnel if its main purpose is to measure rain. Various sizes and shapes of orifice and gauge height are used in different countries, so the measurements are not strictly comparable (WMO, 1989a). The volume or weight of the catch is measured, the latter in particular for solid precipitation. The gauge orifice may be at one of many specified heights above the ground or it can be at the same level as the surrounding ground. The orifice must be placed above the maximum expected depth of snow cover and above the height of significant potential in-splashing from the ground. For solid precipitation measurement, the orifice is above the ground and an artificial shield is placed around it. The most used elevation height in more than 100 countries varies between 0.5 and 1.5 m (WMO, 1989a).

The measurement of precipitation is very sensitive to exposure and particularly to the wind. Following sections discuss exposure and errors to which precipitation gauges are prone, and the corrections that may be applied. Some of the new techniques currently appearing in operational use are not described here (for example, the optical rain gauge, which makes use of optical scattering). Useful sources of information on new methods under development are the reports of recurrent conferences, such as international workshops on precipitation measurement (Slovak hydro- meteorological Institute and Swiss Federal Institute of Technology, 1993; WMO, 1989b) and those organized by the Commission for Instruments and Methods of Observation (WMO, 1998).

Point measurements of precipitation serve as the primary source of data for aerial analysis. However, even the best measurement of precipitation at a given point is only representative of a limited area, the size of which factors in the length of accumulation period, the physiographic homogeneity of the region, local topography, and the precipitation-producing process. Radar and, more recently, satellites are used to define and quantify the spatial distribution of precipitation. The techniques are described in Part II of this Guide. In principle, a suitable integration of all three sources of aerial precipitation data into national precipitation networks (automatic gauges, radar, and satellite) can be expected to provide sufficiently accurate aerial precipitation estimates on an operational basis for a wide range of precipitation data users. Instruments that detect precipitation and identify its type, as distinct from measuring it, may be used as present weather detectors.

1.3 Reference Gauges and Inter-comparisons

Several types of gauges have been used as reference gauges. The main feature of their design is to reduce or control the effect of wind on the catch, which is the most serious reason for differences in behavior of gauges. They are also chosen so as to reduce the other errors. Ground-level gauges are used as reference gauges for liquid precipitation measurement. Because of the absence of wind-induced error they generally show more precipitation than any elevated gauge (WMO, 1984). The gauge is placed in a pit with the gauge rim at ground level, sufficiently distant from the nearest edge of the pit to avoid in-splashing. A strong plastic or metal anti-splash grid with a central opening for the gauge should span the pit. Provision should be made for draining the pit. As shown in Figure 1.

Figure 1-1 Inter-comparison laboratory experiment for a tipping-bucket rainfall

1.4 Documentation

The measurement of precipitation is particularly sensitive to gauge exposure, so metadata about the measurements must be recorded meticulously to compile a comprehensive station history, to be available for climate and other studies, as well as quality assurance. Section 6.2 discusses the site information that must be kept: detailed site descriptions, including vertical angles to significant obstacles around the gauge, gauge configuration, height of the gauge orifice above ground and height above ground of the wind speed measuring instrument. Changes in observational techniques of precipitation, mainly the exchange of precipitation gauge types, moving the gauge site, or change of installation height can cause temporal in-homogeneities in precipitation time-series. The use of differing types of gauges and site exposures causes spatial in-homogeneities. This is due to the systematic errors of precipitation measurement, mainly wind-induced error. Since adjustment techniques based on statistics can remove the in-homogeneities relative to the measurements of surrounding gauges, the correction of precipitation measurements for the wind-induced error can eliminate the bias of measured values of any type of gauge. The following sections on the various instrument types discuss the corrections that may be applied to precipitation measurements. Such corrections have uncertainties, and the original records and the correction formulae should be kept. Any changes in the methods of observation should also be documented.

1.5 Siting and Exposure

Any method of measuring precipitation should aim to obtain a sample that is representative of the true amount falling over the area, which the measurement is intended to represent, whether on the synoptic, meso- or micro- scale. The choice of site, as well as systematic errors in measurement, are therefore important. For a discussion of the effects of the site, see Sevruk and Zahlavova (1994). The location of precipitation stations within the area of interest is important, because the number and locations of the gauge sites determine how well the measurements represent the actual amount of precipitation falling in the area. The effects on the wind field of the immediate surroundings of the site can give rise to local excesses and deficiencies of precipitation. In general, objects should not be closer to the gauge than a distance twice their height above the gauge orifice. For each site, the average vertical angle of obstacles should be estimated, and a site plan should be made. Sites on a slope or on the roof of a building should be avoided. Sites selected for measurement of snowfall and/or snow cover should be in areas sheltered from the wind as much as possible. The best sites are often found in clearings within forests or orchards, among trees, in scrub or shrub forests, or where other objects act as an effective wind-break for winds from all directions. Preferably, however, the effects of the wind, and of the site on the wind, can be reduced by using a ground-level gauge for liquid precipitation or by making the airflow horizontal above the gauge orifice using the following techniques. These are listed in order of decreasing effectiveness: (a) In areas having homogeneous dense vegetation, the height of such vegetation should be kept at the same level as the gauge orifice by regular clipping; (b) In other areas, by simulating the effect in (a) by the use of appropriate fence structures; (c) By using wind shields around the gauge. The surface surrounding the precipitation gauge can be covered with short grass, gravel, or shingle, but hard, flat surfaces, such as concrete, should be avoided, to prevent excessive in splashing.

Seiber and Morén studied the systematic errors due to aerodynamic effects, and wetting losses are known to bias point measurements of precipitation as shown in Figure (2). In their study project, a rain gauge with a new type of wind shield and a special weighing construction is used to minimize these errors. The wind shield consists of a flange surrounding the gauge at the level of the orifice. The idea was to screen the area above the orifice from the disturbance of the wind field by the gauge. At different locations the measured precipitation amounts were compared with the amounts caught by standard gauges. The analysis showed that the catch of the new gauge was higher than that of the standard gauges. A difference of about 3% was related to reduced wind-induced losses, while a difference of about 0.25 mm per event was explained as elimination of wetting loss. At one location, the differences were related to wind speed and rainfall intensity to evaluate the effect of the wind shield. The relative differences were largest (20%) for events with low intensity and high wind speed.

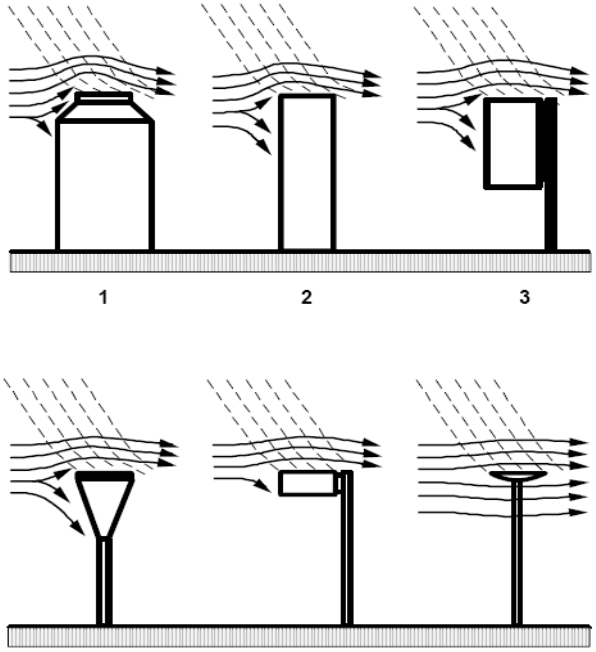


Figure 1-2 Different shapes of standard precipitation gauges. Solid line shows streamlines and dashed line the trajectories of precipitation particles. The first gauge shows the largest wind field deformation above the gauge orifice and the last gauge the smallest. Consequently, the wind-induced error for the first gauge is larger than for the last gauge

1.6 Errors and corrections in precipitation gauges

It is appropriate to discuss at this point the errors and corrections that apply in some degree to most precipitation gauges, whether recording or non-recording. Comprehensive accounts of errors and corrections can be found in WMO, 1982, 1984, 1986 and, specifically for snow, in WMO, 1998). Details of the models currently used for adjusting raw precipitation data in Canada, Denmark, Finland, Russia, Switzerland and the United States are given in WMO, 1982. WMO, 1989a gives a description of how the errors occur. The amount of precipitation measured by commonly used gauges may be less than the actual precipitation reaching the ground by up to 30 percent or more. Systematic losses will vary by type of precipitation (snow, mixed snow and rain, and rain). The systematic error of measurement of solid precipitation is commonly large and may be of a magnitude greater than those normally associated with measurements of liquid precipitation. For many hydrological purposes, it is necessary first to make adjustments to the data in order to allow for error prior to making the calculations. The adjustments cannot, of course, be exact (and may even make things worse). Thus, the original data should always be kept as basic archives both to maintain continuity and to serve as the best base for future improved adjustments if, and when, they become possible. The true amount of precipitation may be estimated by correcting for some or all of the various error terms listed below:

- Error due to systematic wind-field deformation above the gauge orifice: typically 2 to 10 percent for rain and
- 10 to 50 percent for snow;
- Error due to wetting loss on the internal walls of the collector;
- Error due to wetting loss in the container when it is emptied: typically 2 to 15 percent in summer and 1 to 8 percent in winter, for (b) and (c) together;

- Error due to evaporation from the container (most important in hot climates): 0 to 4 percent;
- Error due to blowing and drifting snow;
- Error due to the in- and out-splashing of water: 1 to 2 percent;
- Random observational and instrumental errors, including incorrect gauge reading times.

The first six error components are systematic and are listed in order of general importance. The net error due to blowing and drifting snow and to in- and out-splashing of water can be either negative or positive, while net systematic errors due to the wind field and other factors are negative. Since the errors listed as (e) and (f) above are generally difficult to quantify, the general model for adjusting the data from most gauges takes the following form:

$$\mathbf{Pk = kPc = k\,(Pg + \Delta P1 + \Delta P2 + \Delta P3)}$$

where Pk is the adjusted precipitation amount, k is the adjustment factor for the effects of wind field deformation, Pc is the amount of precipitation caught by the gauge collector, Pg is the measured amount of precipitation in the gauge, ΔP1 is the adjustment for the wetting loss on the internal walls of the collector, ΔP2 is the adjustment for wetting loss in the container after emptying, and ΔP3 is the adjustment for evaporation from the container. The corrections are applied to daily or monthly totals or, in some practices, to individual precipitation events. In general, the supplementary data needed to make such adjustments include the wind speed at the gauge orifice during precipitation, drop size, precipitation intensity, air temperature and humidity, and characteristics of the gauge site. Wind speed and precipitation type or intensity may be sufficient variables to determine the corrections. Wind speed alone is sometimes used. At sites where such observations are not made, interpolation between those observations made at adjacent sites may be used for making such adjustments, but with caution, and for monthly rainfall data only. For most precipitation gauges, wind speed is the most important environmental factor contributing to the under-measurement of solid precipitation. These data must be derived from standard meteorological observations at the site in order to provide daily adjustments. In particular, if wind speed is not measured at gauge orifice height, it can be derived by using a mean wind speed reduction procedure after having knowledge of the roughness of the surrounding surface and the angular height of surrounding obstacles. A suggested scheme is shown in Annex 6.B2. This scheme is very site-dependent and estimation requires a good knowledge of the station and gauge location. Shielded gauges catch more precipitation than their unshielded counterparts, especially for solid precipitation. Therefore, gauges should be shielded either naturally (e.g. forest clearing) or artificially (e.g. Alter, Canadian Nipher type, Tretyakov wind shield) to minimize the adverse effect of wind speed on measurements of solid precipitation (refer WMO, 1994 and 1998 for some information on shield design). Wetting loss (Sevruk, 1974a) is another cumulative systematic loss from manual gauges which varies with precipitation and gauge type; its magnitude also depends on the number of times the gauge is emptied. Average wetting loss can be up to 0.2 mm per observation. At synoptic stations where precipitation is measured every six hours, this can become a very significant loss. In some countries, wetting loss has been calculated to be 15–20 percent of the measured winter precipitation. Correction for wetting loss at the time of observation is a feasible alternative. Wetting loss can be kept low in a well-designed gauge. The internal surfaces should be of a material which can be kept smooth and clean; paint, for example, is unsuitable but baked enamel is satisfactory. Seams in construction should be minimized. Evaporation losses (Sevruk, 1974b) vary by gauge type, climatic zone and time of year. Evaporation loss is a problem with gauges that do not have a funnel device in the bucket, especially in late spring in mid-latitudes. Losses of over 0.8 mm per day have been reported. Losses during winter are much less than during comparable summer months, 2 A wind reduction scheme recommended by the eleventh session of the Commission for Instruments and Methods of Observation, 1994.

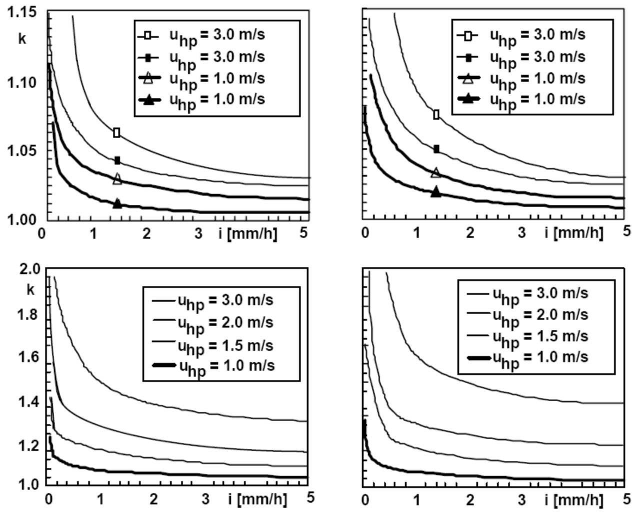


Figure 3 k factor for precipitation

As shown in Figure 3, conversion factor k defined as the ratio of "correct" to measured precipitation for rain (top) and snow (bottom) for two unshielded gauges in dependency on wind speed uhp, intensity i and type of weather situation according to Nespor and Sevruk (1999). Left is the German Hellmann, manual standard gauge and right the recording, tipping-bucket gauge by Lambrecht. Void symbols in the top diagrams refer to orographic rain and black ones to showers. Note different scales for rain and snow. For shielded gauges, k can be reduced to 50 and 70 percent for snow and mixed precipitation, respectively (WMO, 1998).

The heated losses are not considered in the diagrams (in Switzerland they vary with altitude between 10 and 50 percent of measured values of fresh snow) ranging from 0.1–0.2 mm per day. These losses, however, are cumulative. In a well-designed gauge, only a small water surface is exposed, its ventilation is minimized, and the water temperature is kept low by a reflective outer surface. It is clear that, in order to achieve data compatibility when using different gauge types and shielding during all weather conditions, corrections to the actual measurements are necessary. In all cases where precipitation measurements are adjusted in an attempt to reduce errors, it is strongly recommended that both the measured and adjusted values be published.

1.7 Recording precipitation gauges

Automatic recording of precipitation has the advantage that it can provide better time resolution than manual measurements, and it is possible to reduce the evaporation and wetting losses. They are, of course, subject to the wind effects discussed in section 6.4. Three types of automatic precipitation recorder are in general use: the weighing-recording type, the tilting or tipping-bucket type, and the float type. Only the weighing type is satisfactory for measuring all kinds of precipitation, the use of the other two types being for the most part limited to the measurement of rainfall. Some new automatic gauges that measure precipitation without moving parts are available. These gauges use devices such as capacitance probes, pressure transducers, and optical or small radar devices to provide an electronic signal that is proportional to the precipitation equivalent. The clock device that times intervals and dates the time record is a very important component of the recorder.

1.7.1 Weighing-recording gauge

1.7.1.1 Instruments

In these instruments, the weight of a container, together with the precipitation accumulated therein, is recorded continuously, either by means of a spring mechanism or with a system of balance weights. All precipitation, both liquid and solid, is recorded as it falls. This type of gauge normally has no provision for emptying itself; the capacity (i.e. maximum accumulation between recharges) ranges from 150 to 750 mm. The gauges must be maintained to minimize evaporation losses, which can be accomplished by adding sufficient oil or other evaporation suppressants to the container to form a film over the water surface. Any difficulties arising from oscillation of the balance in strong winds can be reduced with an oil damping mechanism or, if recent work is substantiated, by suitably programming a microprocessor to eliminate this effect on the readings. Such weighing gauges are particularly useful for recording snow, hail, and mixtures of snow and rain, since the solid precipitation does not require melting before it can be recorded. For winter operation, the catchments container is charged with an antifreeze solution to dissolve the solid contents. The amount of antifreeze depends on the expected amount of precipitation and the minimum temperature expected at the time of minimum dilution. The weight of the catchments container, measured by a calibrated spring, is translated from a vertical to an angular motion through a series of levers or pulleys. This angular motion is then communicated mechanically to a drum or strip chart or digitized through a transducer. The accuracy of these types of gauges is related directly to their measuring and/or recording characteristics which can vary with the manufacturer.

1.7.1.2 Errors and Corrections

Except for error due to the wetting loss in the container when it is emptied, weighing-recording gauges are susceptible to all the other sources of error discussed in section 6.4. It should also be noted that automatic recording gauges alone cannot identify the type of precipitation. A significant problem with this type of gauge is that precipitation, particularly freezing rain or wet snow can stick to the inside of the orifice of the gauge and not fall into the bucket until some time later. This severely limits the ability of weighing-recording gauges to provide accurate timing of precipitation events. Another common fault with weighing type gauges is wind pumping. This usually occurs during high winds when turbulent air currents passing over and around the catchments' container cause oscillations in the weighing mechanism. By using programmable data logging systems, errors associated with such anomalous recordings can be minimized by averaging readings over short-time intervals, i.e. one minute. Timing errors in the instrument clock may assign the catch to the wrong period or date. Some potential errors in manual methods of precipitation measurement can be eliminated or at least minimized by using weighing-recording gauges. Random errors in measurement associated with human observer error and certain systematic errors, particularly evaporation and wetting loss, are minimized. In some countries, trace observations are officially given a value of zero, thus resulting in a biased underestimate of the seasonal precipitation total. This problem is minimized with weighing type gauges, since even very small amounts of precipitation will accumulate over time. The correction of weighing gauge data on an hourly or daily basis may be more difficult than on longer time periods, such as monthly climatologically summaries. Ancillary data from the automatic weather stations, such as wind at gauge height, air temperature, present weather or snow depth, will be useful in interpreting and correcting accurately the precipitation measurements from automatic gauges.

1.7.1.3 Calibration and Maintenance

Weighing-recording gauges usually have few moving parts and, therefore, should seldom require calibration. Calibration commonly involves the use of a series of weights which, when placed in the bucket or catchments container, provide a predetermined value equivalent to an amount of precipitation. Calibrations should normally be done in a laboratory setting and should follow the manufacturer's instructions. Routine maintenance should be done every three to four months depending on precipitation conditions at the site. Both exterior and interior of the gauge should be inspected for loose or broken parts and to ensure that the gauge is level. Any manual read-out should be checked against the removable data record to ensure consistency before removing and annotating the record. The bucket or catchment container should be emptied, inspected, cleaned if required, and recharged with oil for rainfall-only operation or with antifreeze and oil if solid precipitation is expected. The recording device should be set to zero in order to make maximum use of the gauge range. The tape, chart supply or digital memory, as well as the power supply, should be checked and replaced, if required. A volt-ohmmeter may be required to set the gauge output to zero when a data logger is used or to check the power supply of the gauge or recording system. Timing intervals and dates of record must be checked.

1.7.2 Tipping-bucket gauge

The tipping-bucket rain gauge is used for measuring accumulated totals and the rate of rainfall but does not meet the accuracy requirements because of large nonlinear errors, particularly at high precipitation rates.

1.7.2.1 Instrument

The principle behind the operation of this instrument is simple. A light metal container or bucket divided into two compartments is balanced in unstable equilibrium about a horizontal axis. In its normal position, the bucket rests against one of two stops, which prevents it from tipping over completely. Rain water is conducted from a collector into the uppermost compartment and, after a predetermined amount has entered the compartment, the bucket becomes unstable and tips over to its alternative rest position. The bucket compartments are shaped in such a way that the water is emptied from the lower one. Meanwhile subsequent rain falls into the newly positioned upper compartment. The movement of the bucket as it tips can be used to operate a relay contact to produce a record consisting of discontinuous steps; the distance between each step on the record represents the time taken for a specified small amount of rain to fall. This amount of rain should not exceed 0.2 mm if detailed records are required. The bucket takes a small but finite time to tip and, during the first half of its motion, additional rain may enter the compartment that already contains the calculated amount of rainfall. This error can be appreciable during heavy rainfall (250 mm hr-1), but it can be controlled. The simplest method is to use a device like a siphon at the foot of the funnel to direct the water to the buckets at a controlled rate. This smoothes out the intensity peaks of very short-period rainfall. Alternatively, a device could be added to accelerate the tipping action; essentially, a small blade is impacted by the water falling from the collector and is used to apply an additional force to the bucket, varying with rainfall intensity. The tipping-bucket gauge is particularly convenient for automatic weather stations because it lends itself to digital methods. The pulse generated by a contact closure can be monitored by a data logger and totaled over selected time periods to provide precipitation amount. It may also be used with a chart recorder.

1.7.2.2 Errors and Corrections

Tipping-bucket rain gauges have sources of error somewhat different from other gauges, so special precautions and corrections are advisable. Some sources of error include:

- The loss of water during the tip in heavy rain can be minimized but not eliminated;
- With the usual design of the bucket, the exposed water surface is large in relation to its volume so that appreciable evaporation losses can occur, especially in hot regions. This error may be significant in light rain;
- The discontinuous nature of the record may not provide satisfactory data during light drizzle or very light rain. In particular, the time of onset and cessation of precipitation cannot be accurately determined;

- Water may adhere to both the walls and the lip of the bucket resulting in rain residue in the bucket and additional weight to be overcome by the tipping action. Tests on waxed buckets produced a 4 percent reduction in the volume required to tip the balance over non-waxed buckets. Volumetric calibration can change, without adjustment of the calibration screws, by variation of bucket wettability through surface oxidation or contamination by impurities and variations in surface tension;
- The stream of water falling from the funnel onto the exposed bucket may cause over-reading, depending on the size, shape and position of the nozzle;

The instrument is particularly prone to bearing friction and improper balancing of the bucket due to the gauge not being level. Careful calibration can provide corrections for the systematic parts of these errors. The measurements from tipping-bucket rain gauges may be corrected for effects of exposure, as for other types of precipitation gauges. Heating devices can be used to allow for measurements during the cold season, particularly of solid precipitation. However, the performance of heated tipping-bucket gauges has been found to be very poor as a result of large errors due to both wind and evaporation of melting snow. Therefore, these types of gauges are not recommended for use in winter precipitation measurement in regions where temperatures fall below 0°C for prolonged periods of time.

1.7.2.3 Calibration and Maintenance

Calibration of the tipping-bucket is usually accomplished by passing a known amount of water through the tipping mechanism at various rates and by adjusting the mechanism to the known volume. This procedure should be done under laboratory conditions. Due to the many error sources, the collection characteristics and calibration of tipping-bucket rain gauges are a complex interaction of many variables. Daily comparisons with the standard rain gauge can provide useful correction factors and is good practice. The correction factors may vary from station to station. Correction factors are generally greater than 1.0 (under-reading) for low intensity rain, and less than 1.0 (over-reads) for high intensity rain. The relationship between the correction factor and intensity is not linear but forms a curve.

1.7.3 Float gauge

In this type of instrument, the rain passes into a float chamber containing a light float. As the level of the water within the chamber rises, the vertical movement of the float is transmitted, by a suitable mechanism, to the movement of a pen on a chart or a digital transducer. By suitably adjusting the dimensions of the collector orifice, the float, and the float chamber, any desired chart scale can be used. In order to provide a record over a useful period (24 hours is normally required) either the float chamber has to be very large (in which case, a compressed scale on the chart or other recording medium is obtained), or a mechanism must be provided for automatically and quickly emptying the float chamber whenever it becomes full, so that the chart pen or other indicator returns to zero. Usually, a siphoning arrangement is used. The actual siphoning process should begin precisely at the predetermined level with no tendency for the water to dribble over at either the beginning or the end of the siphoning period, which should not be longer than 15 s. In some instruments, the float chamber assembly is mounted on knife edges so that the full chamber overbalances; the surge of the water assists in the siphoning process and, when the chamber is empty, it returns to its original position. Other rain recorders have a forced siphon which operates in less than five seconds. One type of forced siphon has a small chamber which is separate from the main chamber and which accommodates the rain that falls during siphoning. This chamber empties into the main chamber when siphoning ceases, thus ensuring a correct record of total rainfall. A heating device (preferably controlled by a thermostat) should be installed inside the gauge if there is the possibility that water might freeze in the float chamber during the winter. This will prevent damage to the float and float chamber and will enable precipitation to be recorded during that period. A small heating element or electric lamp is suitable where a main supply of electricity is available, otherwise other sources of power may be employed. One convenient method uses a short heating strip wound around the collecting chamber and connected to a large capacity battery. The amount of heat supplied should be kept to the minimum necessary to prevent freezing, because the heat may reduce the accuracy of the observations by stimulating vertical air movements above the gauge and by increasing evaporation losses. A large under-catch by unshielded heated gauges, caused by the wind and the evaporation of melting snow, has been reported in some countries, as is the case for weighing gauges. With the exception that calibration is performed by using a known volume of water, maintenance of this gauge is similar to the weighing-recording gauge.

1.8 Precipitation Inter-comparison Sites

The Commission for Instruments and Methods of Observation, at its eleventh session held in 1994, made the following statement regarding precipitation inter-comparison sites: The Commission recognized the benefits of national precipitation sites or centers where past, current and future instruments and methods of observation for precipitation can be assessed on an ongoing basis at evaluation stations. These stations should:

- Operate the WMO recommended gauge configurations for rain (pit gauge) and snow (Double Fence Inter-comparison Reference (DFIR)). Installation and operation will follow specifications of the WMO precipitation inter-comparisons. A DFIR installation is not required when only rain is observed;
- Operate past, current, and new types of operational precipitation gauges or other methods of observation according to standard operating procedures and evaluate the accuracy and performance against WMO recommended reference instruments;
- Make auxiliary meteorological measurements, which will allow the development and tests for the application of precipitation correction procedures;
- Provide quality control of data and archive all precipitation inter-comparison data, including the related meteorological observations and the metadata, in a readily acceptable format, preferably digital;
- Operate continuously for a minimum of 10 years;
- Test all precipitation correction procedures available (especially those outlined in the final reports of the WMO Inter-comparisons) on the measurement of rain and solid precipitation;
- Facilitate the conduct of research studies on precipitation measurements. It is not expected that the centers provide calibration or verification of instruments. They should make recommendations on national observation standards and should assess the impact of changes in observational methods on the homogeneity of precipitation time-series in the region. The site would provide a reference standard for calibrating and validating radar or remote-sensing observations of precipitation.

1.9 Suggested Correction Procedures for Precipitation Measurements

The Commission for Instruments and Methods of Observation, at its eleventh session held in 1994, made the following statement regarding the correction procedures for precipitation measurements: The correction methods are based on simplified physical concepts as presented in the Instruments Development Inquiry. They depend on the type of precipitation gauge applied. The effect of wind on a particular type of gauge has been assessed by using inter-comparison measurements with the WMO reference gauges — the pit gauge for rain and the Double Fence Inter-comparison Reference (DFIR) for snow as is shown in the International Comparison of National Precipitation Gauges with a Reference Pit Gauge and by the preliminary results of the WMO Solid Precipitation Measurement Inter-comparison. The reduction of wind speed to the level of the gauge orifice should be made according to the following formula:

$$\mathbf{uhp = (\log hzo-1) \cdot (\log Hzo-1)-1 \cdot (1 - 0.024\alpha)\, uH}$$

where uhp is the wind speed at the level of the gauge orifice, h is the height of the gauge orifice above ground, zo is the roughness length (0.01 m for winter and 0.03 m for summer), H is the height of the wind speed measuring instrument above ground, uH is the wind speed measured at the height H above ground, and α is the average vertical angle of obstacles around the gauge. The latter depends on the exposure of the gauge site and can be based either on the average value of direct measurements, on one of the eight main directions of the wind rose of the vertical angle of obstacles (in 360°) around the gauge, or on the classification of the exposure using metadata as stored in the archives of Meteorological Services. The classes are as follows: Class Angle Description

- Exposed site 0–5 Only a few small obstacles such as bushes, groups of trees, a house;
- Mainly exposed site 6–12 Small groups of trees or bushes or one or two houses
- Mainly protected site 13–19 Parks, forest edges, village centers, farms, groups of houses, yards;
- Protected site 20–26 Young forest, small forest clearing, park with big trees, city centers, closed deep valleys, strongly rugged terrain, leeward of big hills

Wetting losses occur with the moistening of the inner walls of the precipitation gauge. They depend on the shape and the material of the gauge, as well as on the type and frequency of precipitation.

Chapter 2. SANA'A BASIN PREVIOUS AND CURRENT WEATHER AND RAINFALL MONITORING SYSTEMS

2.1 Introduction

The literature review revealed that about 24 rainfall stations have been installed in the area of Sana’a Basin since 1970. Fifteen (15) of these stations were installed at different locations within the basin area while 9 others were installed outside the Sana’a Basin boundary at a close distance from that boundary. These stations were installed through the support of different projects over the 36-year time period. Review of the reliability of these stations showed that none of them has continuous records for the whole of the 36 years. Some of these stations recorded rainfall over a two-year period, others recorded for a five-year period and, in most of the stations, the longest recording period was seven years. In addition, the review showed that the longest recorded period from a specific station was 22 years, at Al-Salf station. On the other hand, Sana’a Basin is located in a semi-arid zone, having a very complex topography with a significant variation in the rainfall intensity and rainy days. In the north-eastern part of the basin the rain intensity reaches 170 mm/year while at the south-western it reaches to 330 mm/year. In addition, the nature of the spatial distribution of rainfall over the basin varies drastically from one location to another. Thus, the need for a robust rainfall monitoring network for the entire basin, which has an area of f 3200 km^2 is indispensable to generating reliable information one rainfall and weather in the Sana'a Basin.

Figure 2-1 A Layout Map for Sana'a Basin

Table 2 presents the reliable recording times for the 24 stations reviewed. It can be easily concluded that, to date, only 9 stations have continuous records since 2003; those stations were installed by NWRA. Also, this table demonstrates the continuity of performance for the rainfall recording system within the basin for the last 36 years. The short recording periods for most of the stations are common phenomena due to the previous improper management system. The system was adjusted starting in 2003, since the installation of new rainfall stations by NWRA-SB. From that date on, regular monitoring was performed for the entire Sana'a Basin. An evaluation of these stations conducted by the project included physical status of the station, data collection procedure, maintenance of the stations, access to the stations and reliability of the collected data. The following is a description of these items.

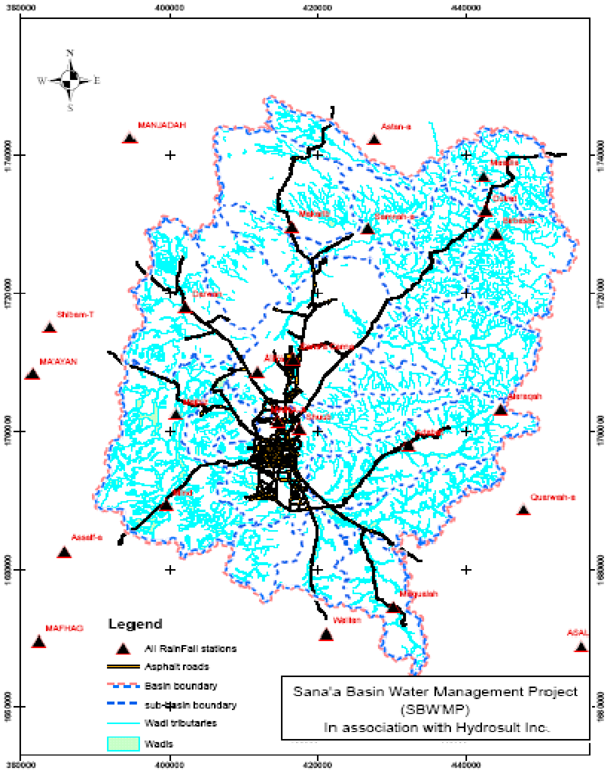


Figure 2-2 Map showing the location of all rainfall stations that were installed within and at the vicinity of Sana'a Basin from 1970 to 2006

Station	Year																																				
	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	0	1	2	3	4	5	6
Adabat			▨	▨	▨	▨	▨	▨	▨	▨																											
Alaraqah														▨	▨																						
Alirra																	▨	▨	▨	▨	▨	▨	▨														
Al-Kherabah																																		▨	▨	▨	▨
Asalf-a									▨	▨	▨	▨			▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Astan-a																						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Bani-Sabira																									▨	▨											
Birbasla																						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨					
Darsalm																																		▨	▨	▨	▨
Darawan			▨	▨	▨	▨	▨	▨	▨	▨																								▨	▨	▨	▨
Dutrat														▨	▨																						
Maadia																						▨	▨	▨	▨	▨	▨	▨									
Majhiz														▨	▨																						
Makarib														▨	▨	▨																					
Maqualah														▨	▨	▨																		▨	▨	▨	▨
Mind			▨	▨	▨	▨	▨	▨	▨	▨																								▨	▨	▨	▨
NWRA-a																				▨	▨	▨	▨	▨										▨	▨	▨	▨
NWRA-b																																		▨	▨	▨	▨
Qarwah-a																		▨	▨	▨	▨	▨	▨	▨						▨	▨	▨	▨				
Samanaha																						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						
Shibam-T						▨	▨	▨				▨	▨	▨	▨	▨	▨					▨	▨														
Shuub						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																						
Wadi Zahr							▨	▨			▨	▨																									
Wallan										▨	▨	▨	▨	▨	▨	▨	▨					▨	▨														

Table 2-1 Recording period for each station installed within the Basin from 1970 to 2006

2.2 Physical Status of the Rainfall Stations

The current study aims at evaluating the current status of the existing rainfall stations. Accordingly, field visits were performed for all the stations. The stations can be listed as followed:

- Mind rainfall station.
- Darawan rainfall station.
- Arahab climatic station.
- Al-Kherba rainfall station.
- Mgwala rainfall station.
- Shahek rainfall station.
- Dar-Salem rainfall station.
- NWRA Climatic station.
- Arhab rainfall station.

Figures 6 and 7 present maps that show respectively the location of the rainfall and meteorological stations within the basin, which are currently under operation. Field visits for each station were conducted, during which an evaluation of the station operation status was conducted. The stations are located within the basin as presented in Figures 6 and 7, where all the rainfall stations are installed on the roofs of governmental buildings, except for the two climatic stations, which are installed in open areas. As indicated earlier in the Report, it advisable to install stations in an open area away from high mountains or buildings to ensure that the effect of the rain-shadow effect is minimal and that the station represents the real situation. For example, Figure 8 presents a picture for the surrounding area of Mind rain-fall station. Mountains are relatively close compared to the other stations shown in Figures 9 through 14. Other stations' pictures show that each station is located in an open area far enough from any mountainous zone. Also, if a station is located within an urban area, the surrounding buildings should not be higher than two or three stories maximum, as shown in Figures 8 through 14. Thus, the effect of the surrounding buildings on the station results will be insignificant.

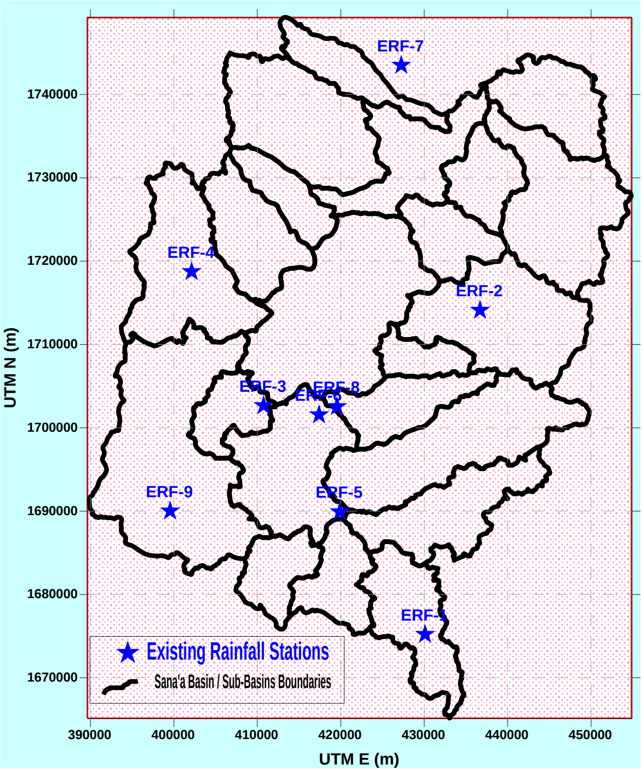


Figure 2-3 Locations of rainfall stations that are currently under operation within Sana'a Basin

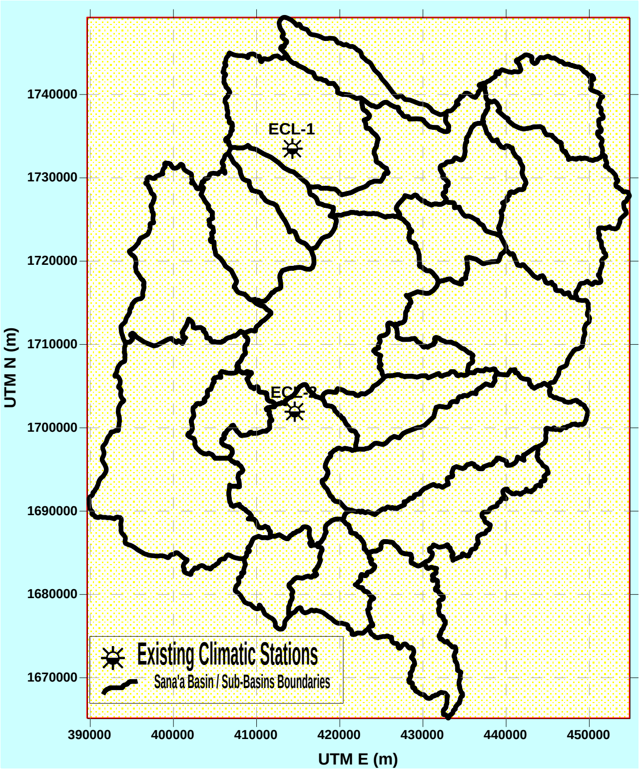


Figure 2-4 Locations of meteorological stations that are currently under operation within Sana'a Basin

Figure 2-5 Mind rainfall station on the top roof of Mind school

Figure 2-6 Darawan rainfall station on the roof of a police station

Figure 2-7 Arhab climatic station inside the university boundary

Figure 2-8 Al-Kherba rainfall station on the roof of a school in Bani-Hashish area

Figure 2-9 Magwala station on the roof of a school

Figure 2-10 Shahek rainfall station on the roof of Shahek school

Figure 2-11 Dar-Salem rainfall station on the top of a school in the area

2.3 Access to the Stations

The stations are installed in urban areas where road access to the stations is mostly paved or reasonably graveled. The stations are usually located on the roofs of schools, police stations, hospitals, etc. It was observed that, where stations are located at public buildings or schools, access to them becomes difficult after office hours or during summer holidays in the case of schools. Figure 15 illustrates how observers collect data in inaccessible locations.

Figure 2-12 Data collectors trying to find an access to the rainfall station that is located on the roof of the school

2.4 Data Collection Procedure

Data are collected by NWRA staff by data loggers connected to a laptop equipped with control software compatible with the station memory unit and data logger system. Figure 16 shows the memory unit metal box that is usually attached to the rainfall station and contains the data logger unit. Figure 17 and Figure 18 present the procedure of data collection that starts by pulling out the memory unit from the steel box and then connects it to the laptop. The software is capable of controlling the data collection time interval that can be ranged from monthly data points to one minute time steps. Data was collected and analyzed to develop a storm pattern for Sana'a Basin. Preliminary data analysis showed that the data collection system should be re-adjusted to 5-minute time steps since the type of storms resemble the semi-arid-type storms that required smaller time steps to typify them. Accordingly, it was decided to re-adjust the time step to 5 minutes at all stations. Starting with the upcoming rainy season, which starts on March 2007, rainfall data will be collected on a 5-minute time step basis. Analysis of rainfall data will be presented later in this chapter.

Figure 2-13 Metal box containing the data logger

Figure 2-14 Rainfall station data logger (this system is used in all stations)

Figure 2-15 Applied procedure for collecting digital data from rainfall station data logger apartheid

2.5 Maintenance of the Stations

The current system that NWRA staff applies for the regular maintenance for the rainfall stations is considered reliable. The regular maintenance procedure is performed regularly every two months which is the regular time for data collection. The maintenance procedure starts by e removing the top screen that covers the collector funnel, the screen is shown in Figure (19). After removing the screen the first step e is to clean this funnel from any blockage or accumulated debris or dust. Then, by removing the funnel the outlet nozzle is cleaned by a thin wire to remove the dust and fine particles as shown in Figures (21 and 22). A view for the funnel after cleaning is presented in Figure (23). The maintenance procedure continues by cleaning the inside space where the water leveler and electrical connections are found. A thin brush is used to remove the dust from inside the leveler as shown in Figures (24 and 25).

Figure 2-16 Top view of water bucket collector showing the screen

Figure 2-17 Sometimes dusts or insects houses blocks the funnel opening

Figure 2-18 View of the collector funnel

Figure 2-19 Cleaning the nozzle opening at the funnel bottom side

Figure 2-20 Funnel after cleaning then it is ready for re-installed in the station

Figure 2-21 Top view for the water leveler, bubble leveler and electrical board

Figure 2-22 Regular maintenance for the rainfall station is performed by removing the dust from the inside parts of the station

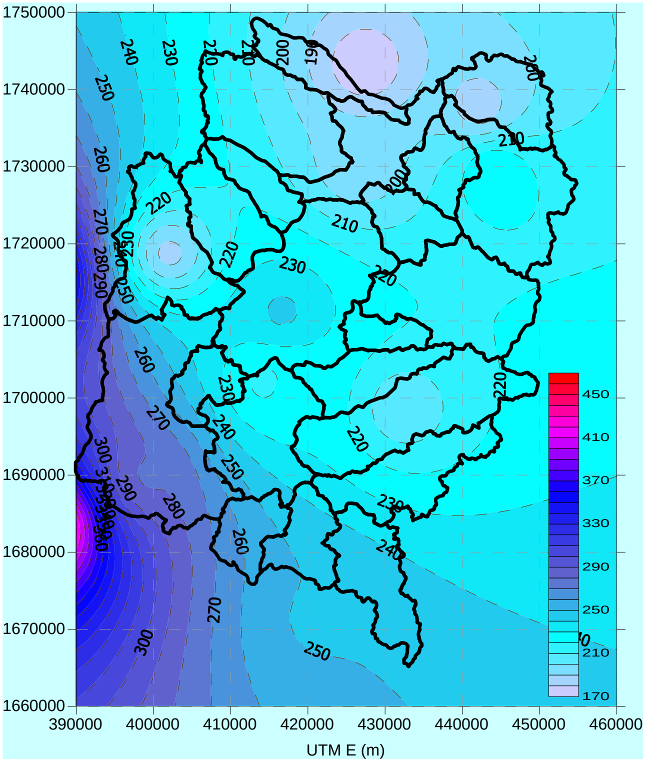
2.6 Calibration of Rain Stations

During the field visits, it was noticed that regular calibration of the stations is not practiced. Recalibration of rainfall stations is essential in order to assure the reading reliability. A program of calibration for the rainfall stations has been prepared for future application in the basin.

Chapter 3. DESIGN A NEW RAINFALL AND WEATHER STATIONS NETWORK WITHIN SANA'A BASIN

3.1 Analysis of Rainfall Data within Sana'a Basin

Rainfall preliminary analysis was performed on the available data for the period 1972 to 2005. Different analyses were performed such as variogram analysis, krigging analysis and residual analyses were e conducted in order to select the most appropriate location for the rainfall and climatic station and to check if the existing locations of the different rainfall station are on the optimal locations in r the basin. Accordingly, the basic isohyetal map for Sana’a Basin was developed and presented in Figure 26.



Error! Reference source not found.

Figure 3-1 Preliminary isohyetale map for Sana'a Basin based on the available data from 1972 to 2005

As shown in this figure the heaviest rains occur at the southern-western part of the basin. While on the north –eastern part of the basin thee maximum value of rainfalls was 380 mm/year and .the minimum value was 180 mm/year.

3.1.1 Cross-Validation

Generally, cross-validation can be considered an objective method of assessing the quality of a grid method, or to compare the relative quality of two or more candidate grid methods. While cross-validation can be used to select a grid method, the results can also be used to assess the spatial variation in grid quality and to guide data sampling. A generalized discussion of cross variation is given here. Refer to one of the many geo-statistics books for more information.

3.1.2 The Cross-Validation Process

Given the known values at N observation locations in the original data set, cross-validation allows you to assess the relative quality of the grid by computing and investigating the grid errors. These errors are calculated by removing the first observation from the data set, and using the remaining data and the specified algorithm to interpolate a value at the first observation location. Using the known observation value at this location, the interpolation error is computed as:

Error = interpolated value – observed value

Then, the first observation is put back into the data set and the second observation is removed from the data set. Using the remaining data (including the first observation), and the specified algorithm, a value is interpolated at the second observation location. Using the known observation value at this location, the interpolation error is computed as before. The second observation is put back into the data set and the process is continued in this fashion for the third, fourth, fifth observations, etc., all the way through, up to and including observation N. This process generates N interpolation errors. Various statistics computed for the errors can be used as a quantitative, objective measure of quality for the grid method. Thus, cross-validation involves four steps:

- Select a grid method, along with all of the defining parameters.
- For each observation location, interpolate the value using the neighboring data, but not the observation itself.
- Compute the resulting interpolation errors.
- Assess the quality of the selected grid method using various summary statistics of the errors.

Thus, the previous process was performed on the isohyetale map data to perform the residual analysis for Sana'a Basin. Figure 27 presents the residual error analysis within the entire Sana'a Basin. The red color spots indicate the locations where the residual error is relatively high. The green color indicates the locations where minimum values of residual occur. Accordingly, to add more stations within the entire Sana'a Basin the new locations should follow the error residual map. This process will be shown later in this chapter.

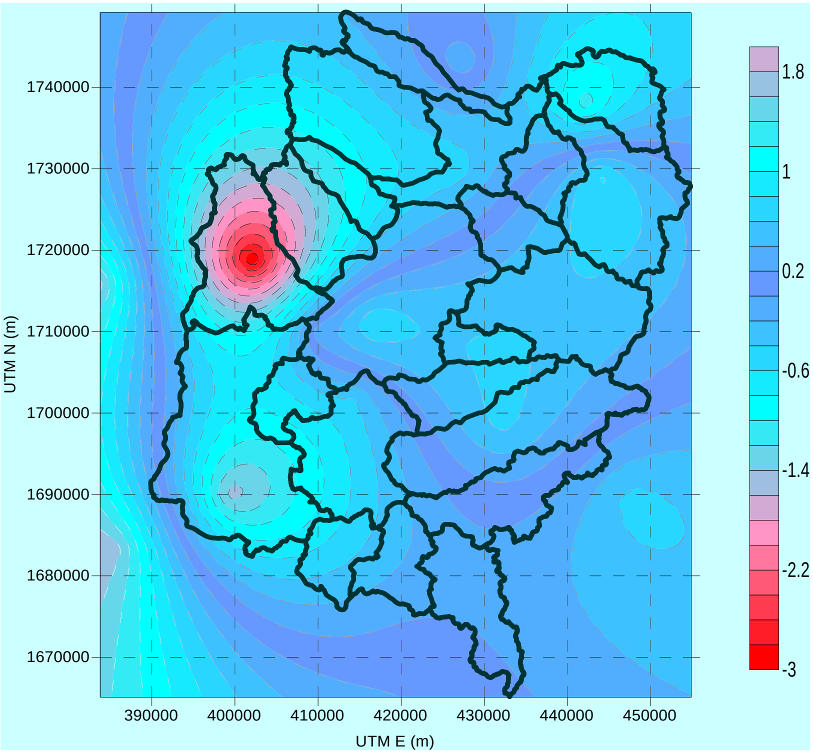


Figure 3-2 Preliminary residuals values between the actual average rainfall data and the krigging estimated rainfall data, high values allocation presents the location of rainfall station needs

3.1.3 Variogram Analysis

The variogram is a measure of how quickly things change on the average. The underlying principle is that, on the average, two observations closer together are more similar than two observations farther apart. Because the underlying processes of the data often have preferred orientations, values may change more quickly in one direction than another. As such, the variogram is a function of direction. The variogram is a three-dimensional function. There are two independent variables (the direction ·, the separation distance *h*) and one dependent variable (the variogram value ·(·,*h*)). When the variogram is specified for krigging, we give the sill, range, and nugget, but we also specify the anisotropy information. The variogram grid is the way this information is organized inside the program. The variogram (XY plot) is a radial slice (like a piece of pie) from the variogram grid, which can be thought of as a "funnel-shaped" surface. This is necessary because it is difficult to draw the three-dimensional surface, let alone try to fit a three-dimensional function (model) to it. By taking slices, it is possible to draw and work with the directional experimental variogram in a familiar form - an XY plot. Remember that a particular directional experimental variogram is associated with a direction. The ultimate variogram model must be applicable to all directions. When fitting the model, the user starts with numerous slices, but must ultimately mentally integrate the slices into a final 3-D model. In addition, if the empirical semi-variogram continues climbing steadily beyond the global variance value, this is often indicative of a significant spatial trend in the variable, resulting in a negative correlation between variable values separated by large lags. Three options for dealing with lag include:

- Fit a trend surface and work with residuals from the trend;
- Try to find a "trend-free" direction and use the variogram in that direction as the variogram for the "random" component of the variable;
- Ignore the problem and use a linear or power variogram. The semi-variogram for the porosity data does not seem to indicate a significant trend.

The variogram analysis for the rainfall isohyetale map was performed and presented in Figure 28. As shown in this figure the variogram analysis is performing oscillations along the entire separating distant. Thus, different variogram models were performed such as the linear, logarithmic, power effect, quadratic, and spherical. However, none of these models was performing reasonable variogram analysis models. **The conclusions can be stated as there is an essential need to add more stations to perform a logic variogram analysis for the basin.**

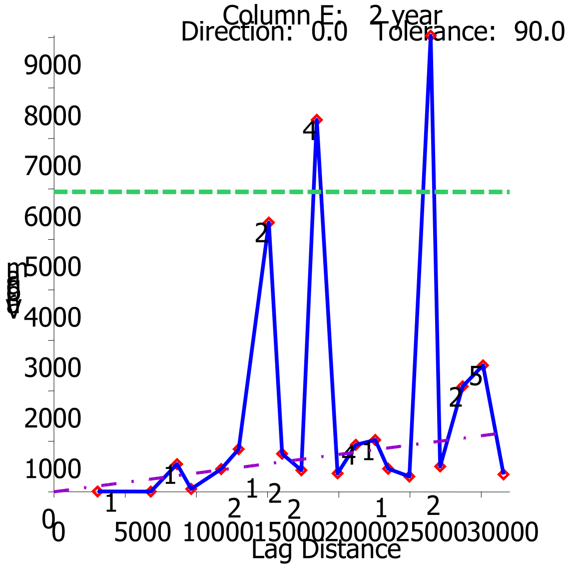


Figure 3-3 Variogram analysis for the rainfall average yearly data from 1972 to 2006

Chapter 4. DESIGN OF NEW WEATHER AND RAINFALL MONITORING STATIONS ALL OVER THE ENTIRE SANA'A BASIN

4.1 Rainfall and Meteorological Stations Network Design

4.1.1 Introduction

It is important to optimize the network to achieve monitoring objectives and to generate reliable data on a cost-effective basis. The planning of a network should be closely related to physiographic set up, precipitation, land use, etc. Various approaches and techniques for designing the network density have been attempted for rainfall stations within the entire Sana’a Basin. So, two techniques were used to develop the rainfall network within the basin. The following is a description of the various approaches followed:

4.1.2 Coefficient of Variation and Error Percentage Method

The optimum number of rainfall monitoring stations is calculated using the following formula:

$$N = \frac{100 \times \sigma_x}{\overline{X}\ P^2} \text{ .... } \mathbf{(1)}$$

where
N = Optimum number of network stations;
X = Mean rainfall intensity all over the basin;
P = Desired degree of percentage error; in the current study, it has been considered to be 5%;
σ_x = Standard error deviation;

Parameter	Value
Cv =	32.92517443
P =	5
Cv^22/P^2=	43.36268446
Opt. # of Stations	44

Table 4-1 Calculations for the optimum number of rainfall stations within Sana’a Basin using coefficient of variation method

4.1.3 Modified Coefficient of Variation and Error Percentage Method

This method relies on a coefficient of variation and error percentage method but an additional parameter has been added, namely s the range of variation of rainfall, thus the following equation can be applied:

$$E = \frac{P \times R}{\overline{X}} \text{ ....} \mathbf{(2)}$$

where
E = Range of error variation;
R = Range of fluctuation of rainfall intensity within the entire basin.

The different parameters used in this analysis are shown in

Parameter	Value
P	5
Range	292.7
Mean	242.34
E	6.039036065
Cv^2/E^2	29.72493561
Opt. # of Stations	30

Table 4-2 Calculations for the optimum number of rainfall stations within Sana'a Basin using the modified method that incorporates the fluctuations of rainfall within Sana'a Basin

4.2 Proposed Locations for New Rainfall and Meteorological Stations

From the statistical analysis it can be concluded that the total number of rainfall stations within the entire basin should be in the range of 30 to 44 rainfall stations. The following criteria are followed for selecting the new stations:

- draw lessons from the residual errors in the exiting rainfall stations analysis;
- consider the location of the existing meteorological and rainfall stations;
- the elevations of the new stations should be extended to the highest and lowest elevations within the basin, thus the relationship between the ground elevation and rainfall intensity can be developed
- distribution of the stations in the different sub-basins.

Field visits to the proposed locations were performed to assign the final location for the new stations. Finally, 35 new rainfall stations and 8 meteorological stations are proposed to present the newly designed monitoring network within Sana'a Basin.

Based on the above-listed criteria. the following tables present the proposed numbers and type of station in the entire basin. It has been found that, in almost all of the 22 sub-basins that are presented in Figure 29, the maximum number of rainfall stations within a sub-basin is to be found at *Iqbal and ash Sha'b* sub-basin since it needs 4 rainfall stations and one meteorological station. Only one sub-basin does not need any additional station, that is *Al-Foros and Rjiam* sub-basin. The total number of climatic stations needed is found to be 8 additional stations and the total number of rainfall stations within the different sub-basins is found to be 31. The preliminary geo-referenced locations were determined for both the rainfall and meteorological stations. Accordingly, the geo-referenced locations for each station have been determined on a geo-referenced map and the geo-referenced xxxxxxx .

4.3 Proposed Stations Elevation

The proposed meteorological and rainfall stations are tested for their fair distribution in the Sana'a Basin, as well as for their minimum and maximum ground elevation. The reason for that is to perform a spatial analysis of rainfall distribution and the effect of ground elevation on the rainfall intensity. The preliminary check shows that any rainfall or meteorological station either existing or newly installed do not represent the highest and lowest elevation in the basin. Accordingly, four more rainfall stations are found to be essential for the data collection in the entire basin. Figure 30 presents the ground elevation for each of the proposed stations and for the existing stations. It can be concluded that the proposed new stations cover a wide range of ground elevation in the basin.

4.4 Initial Proposed Rainfall and Meteorological Network

The final spatial distribution of the proposed network is presented in Table 5. Based on the proposed locations of the new stations, special field visits will be performed to determine the precise location of these stations. Contrary to the recommendations earlier, for safety and sustainability reasons, these stations should be installed on the roof of official buildings such police stations, schools and hospitals. So, a special program to assign a precise location for each station will be conducted through the activity-4 team. Special attention has been given to establishing a special installation plan for proposed new stations.

4.5 Final Rainfall and Meteorological Network

The final meteorological and rainfall monitoring networks have been selected and finalized after field visits to all the locations. Final locations for the meteorological and rainfall stations are listed in Tables 6 and 7 respectively. Figures 31 and 32 illustrate the spatial distribution of the station locations in the Sana'a Basin. Appendix A contains pictures for the final locations of rainfall and meteorological stations.

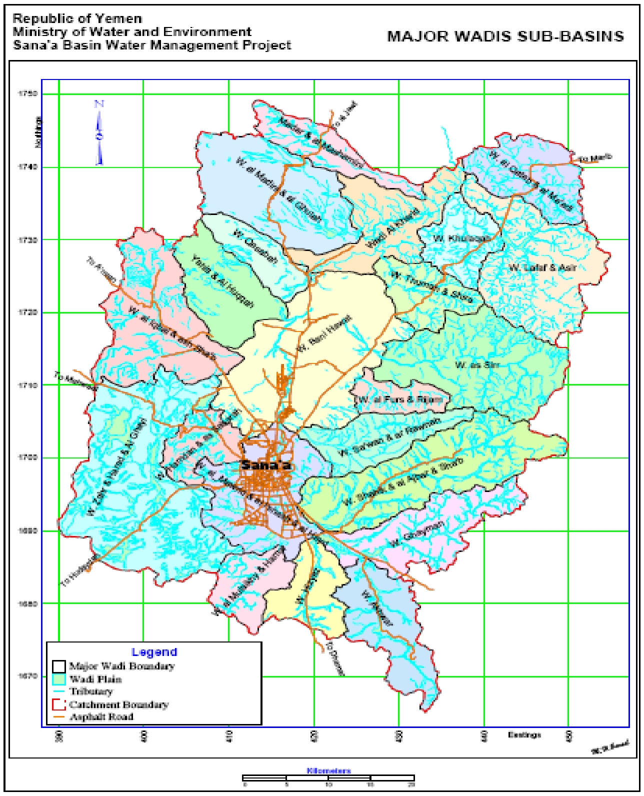


Figure 4-1 Configuration of sub-basins within the entire Sana'a Basin

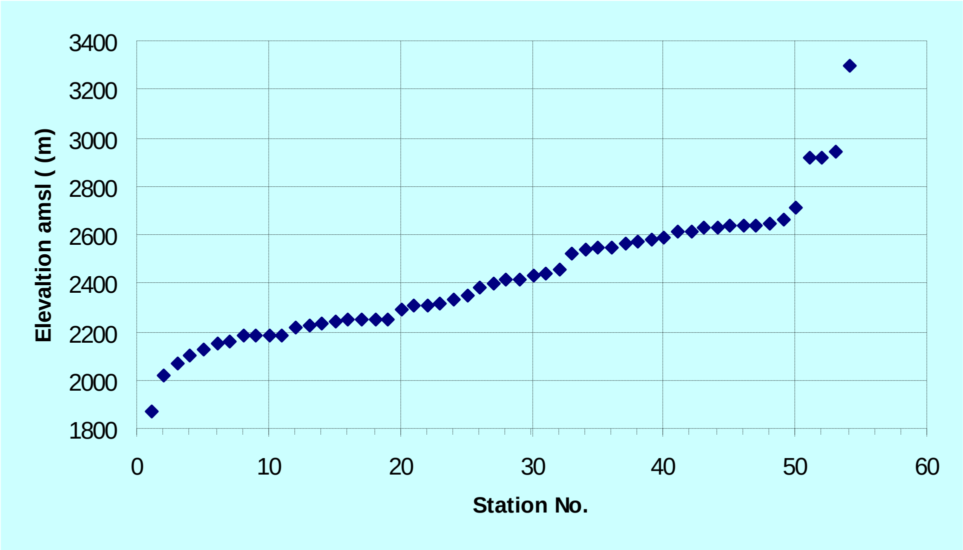


Figure 4-2 **Elevation of proposed and existing rainfall and meteorological stations over the entire Sana'a Basin**

Ser No	Sub-Basin	UTM (E) m	UTM (N) m	Elev (m)	Type	Notice
1	Madani and Al-Ghulah	414310	1733500	2130	Meteo	EX
2	Mawrid and Al-Ishash	414581	1701935	2190	Meteo	EX
3	Akhwar	430100	1675200	2315	RF	EX
4	As-Sirr	436689	1714095	2310	RF	EX
5	Hamadan and Al-Sabarah	410750	1702650	2250	RF	EX
6	Iqbal and ash Sha'b	402126	1718733	2421	RF	EX
7	Madani and Al-Ghulah	419887	1689906	2319	RF	EX
8	Mawrid and Al-Ishash	417400	1701550	2220	RF	EX
9	Out of Sana'a Basin	427250	1743500	2350	RF	EX
10	Sa'wan awa Al-Rawnah	419550	1702540	2445	RF	EX
11	Zahr and Al Al-Ghayl	399550	1690005	2670	RF	EX
12	Al-Kharid	426270	1730770	2023	Meteo	PR
13	Al-Qatab and MA'adi	439270	1741220	2074	Meteo	PR
14	As-Sirr	443170	1711810	2416	Meteo	PR
15	Bani Hawat	423730	1720120	2167	Meteo	PR
16	Hizayaz	418750	1683770	2337	Meteo	PR
17	Iqbal and ash Sha'b	399410	1720120	2460	Meteo	PR
18	Madini and Al Ghulah	407120	1740150	2713	Meteo	PR
19	Zahr and Al Al-Ghayl	399310	1693060	2617	Meteo	PR
20	Akhwar	425500	1680670	2435	RF	PR

Ser No	Sub-Basin	UTM (E) m	UTM (N) m	Elev (m)	Type	Notice
21	Al-Kharid	436760	1740200	1922	RF	PR
22	Al-Qassaba	413150	1727080	2254	RF	PR
23	Al-Qatab and MA'adi	447640	1737230	2249	RF	PR
24	As-Sirr	434840	1709040	2649	RF	PR
25	As-Sirr	433460	1717340	2545	RF	PR
26	As-Sirr	448317	1717491	2922	RF	PR
27	Bani Hawat	415300	1713710	2187	RF	PR
28	Ghayman	426890	1688970	2388	RF	PR
29	Ghayman	435880	1695990	2636	RF	PR
30	Hamadan and Al-Sabarah	402500	1701950	2460	RF	PR
31	Iqbal and ash Sha'b	395920	1714920	2589	RF	PR
32	Iqbal and ash Sha'b	405090	1714750	2253	RF	PR
33	Iqbal and ash Sha'b	399310	1724510	2549	RF	PR
34	Iqbal and ash Sha'b	399310	1729400	2552	RF	PR
35	Khulaga	433630	1731350	2105	RF	PR
36	Lasaf and Asir	442870	1730700	2156	RF	PR
37	Madar and Al Mashamini	413910	1747780	2587	RF	PR
38	Madar and Al Mashamini	427290	1738920	2237	RF	PR
39	Madini and Al Ghulah	416680	1733770	2230	RF	PR
40	Madini and Al Ghulah	413390	1741560	2524	RF	PR
41	Mawrid and Al-Ishash	417190	1701160	2256	RF	PR
42	Mulaikhy and Hamal	410280	1685170	2643	RF	PR
43	Sa'wan and Al-Rawnah	429650	1706790	2639	RF	PR
44	Shahik, Al Ajbar and Sha'b	424640	1616060	2404	RF	PR
45	Shahik, Al Ajbar and Sha'b	434670	1701600	2577	RF	PR
46	Shahik, Al Ajbar and Sha'b	442280	1704190	2949	RF	PR
47	Thuma and Shira	431900	1724090	2186	RF	PR
48	Yahis and Al Haqqah	406130	1722010	2295	RF	PR
49	Yahis and Al Haqqah	404210	1729490	2569	RF	PR
50	Yahis and Al Haqqah	398900	1729610	2186	RF	PR
51	Zahr and Al Al-Ghayl	389690	1691070	3300	RF	PR
52	Zahr and Al Al-Ghayl	394710	1692960	2638	RF	PR
53	Zahr and Al Al-Ghayl	394710	1710250	2633	RF	PR
54	Zahr and Al Al-Ghayl	401100	1683530	2921	RF	PR

RF = Rainfall Stations
PR = Proposed Station
Meteo = Meteorological Station
Ex =Existing Stations

Table 4-3 Geo-referenced locations for the proposed climatic stations within the entire Sana'a Basin

Serial No	Location	UTM E (m)	UTM N (m)
1	Bayt Abo-Nashtan	426492	1730281
2	Bayt Zanbour	433221	1737581
3	Bayt Maa'eed	444562	1712128
4	Bani Assem	423948	1719636
5	Jeel Al-Methaq School	419030	1680296
6	Shahid AbdelKhaliq Azzam School	400733	1719956
7	Bai Rasheed	407742	1740852
8	Ga'a Al-Galad	398033	1692579

Table 4-4 Final locations of all of the proposed meteorological stations

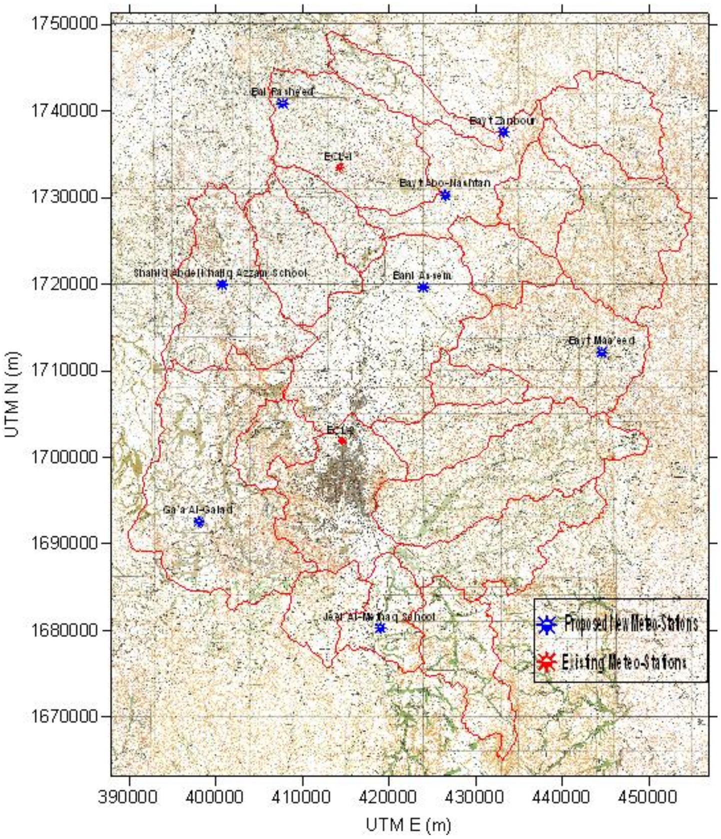


Figure 4-3 Locations of existing and proposed meteorological stations within the entire Sana'a Basin

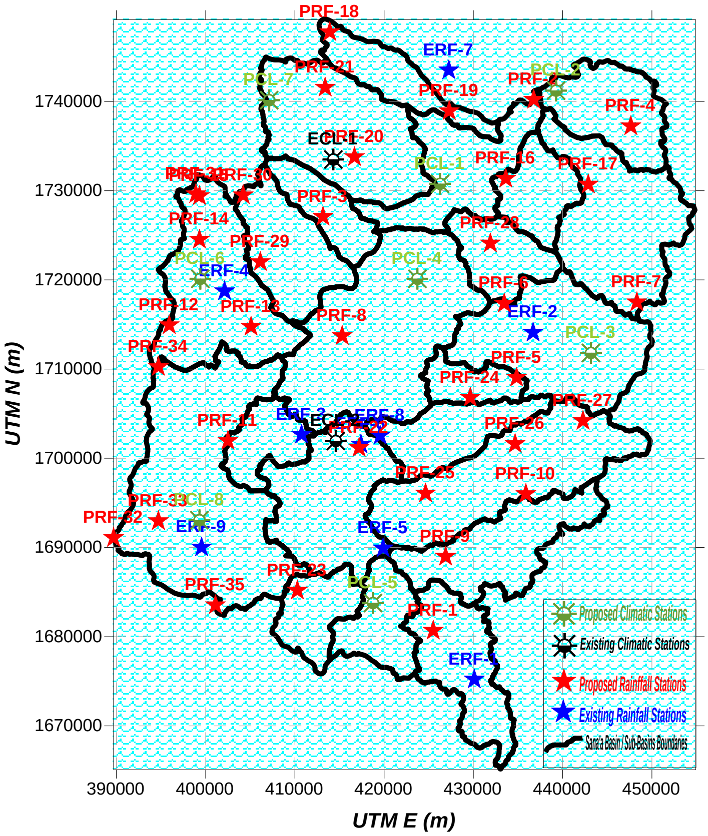


Figure 4-4 **Final Locations of existing and new proposed rainfall and meteorological stations all over the entire Sana'a Basin**

Serial No	Location	UTM E (m)	UTM N (m)
1	Bayt Al-Hamadani	426490	1680302
2	Ghool Ali	440982	1735931
3	Al-Asmaad	413632	1727048
4	Bayt Bani Saber	447759	1737406
5	Al-Oqlaa	433870	1709186
6	Al-Horaa	433752	1719347
7	Shayhan	445648	1718934
8	Bayt Al-Hilaly	415991	1714817
9	Al-Hijraa	428705	1691228
10	Bayt Ogob	433497	1697501
11	Bayt Al-Sa'ebi	400276	1702152
12	Al'eel	398102	1716919
13	Al-Maa'mer	404671	1716735
14	Al-Ga'eef	400272	1725474

Serial No	Location	UTM E (m)	UTM N (m)
15	Al-Ga'eef Al-A'ala	398991	1727865
16	Bayt Araman	434439	1730969
17	Bai Feras	442616	1731381
18	Mahelet Al-Kharid	414219	1747127
19	Bayt Al-Ghedra	425906	1739551
20	Bayt Al-Higari	415420	1735067
21	Bayt Al-Galid	415805	1741187
22	Bayet Al-Ozeri	419303	1722162
23	Bayt Mehfed	411403	1686356
24	Al-Henami	428835	1708637
25	Al-Hisen	425167	1694259
26	Hijrat Alshawkan	437327	1704322
27	Shalal	442893	1703851
28	Mahal Bayt Al-a'anz	432650	1724266
29	Bani Sabe'aa	409137	1723216
30	Bayt Saree'a	407109	1729839
31	Al-Ga'eef Al-A'ala	398991	1727865
32	Bayt Al-Haphash	392117	1692202
33	Al-Masena'a	395245	1695241
34	Al-Mangab	398991	1727865
35	Bayt Regaal	404110	1684747

Table 4-5 Final locations and coordinates of the proposed rainfall stations

APPENDIX A

Pictures for the final locations of rainfall and meteorological stations

Station Type	Selected Site	District	UTM N (m)	UTM E (m)	Elev. m (amsl)
Rainfall	Al Rawd School	Wadi Zahr -Hamdan	1707581	406260	2243
Rainfall	Al Shahied Al Aoqaia School	Lulua'ah - Hamdan	1702413	400802	2506
Rainfall	Al Thawrah School	Sha'asan - Sanhan	1681934	428282	2430
Meteo	Jil Al Mithaq School	Hizyz-Sanhan	1680296	419030	2387
Rainfall	Yemen Mobil Station	Al Lakamah Al Sawda'a - Khawlan	1701619	441867	2613
Rainfall	Al Monaqab School	Al monaqab - Hamdan	1710418	394178	2646
Rainfall	Tozan School	Tozan - Hamdan	1713756	402043	2289
Rainfall	Ali Hamod Al-thib sec. School	Darwan -Hamdan	1716931	404086	2284
Meteo	Al Shahied Abdul Khalik Azan School	Darwan -Hamdan	1719956	400733	2465
Rainfall	Awmar Ebn Abdulaziz School	Huzam -Arhab	1728284	410620	2437
Rainfall	Al jabil School	Wadi Zahr Al Rawd - Bani Al Harith	1708178	406618	2243
Rainfall	Al Sahid Mahmod Handal	Bit Handal - Bani Al Harith	1714829	413631	2200

Table A-1 Some of the selected locations for rainfall and meteorological stations

Figure A-1 School selected for installing the rainfall station (Shaid Mohamed Handal School)

Figure A-2 School selected where the rainfall station will be installed (AL-Jibil School)

Figure A-3 Picture showing one of the schools that was selected for installing the new rainfall station (khairan School)

Figure A-4 Picture showing one of the schools that was selected for installing the new rainfall station Al_Shahied Abdelkhalek Azan School

Figure A-5 Picture showing one of the schools that was selected for installing the new rainfall station (Ali Hamoud Al-Thib School)

Figure A-6 Picture shows one of the schools that was selected for installing the new rainfall station (Tozan School)

Figure A-7 Picture showing one of the schools that was selected for installing the new rainfall station (Sha'asan School)

Figure A-8 **Picture showing one of the schools that was selected for installing the new rainfall station (jeel Al-Meethaq School)**

Figure A-9 **Picture showing one of the schools that was selected for installing the new rainfall station (AL-Shaeed Al-Oqaya School)**

Figure A-10 **Picture showing one of the schools that was selected for installing the new Climatic station (Yemen Mobile Tower Station)**