Food and Agriculture Organization
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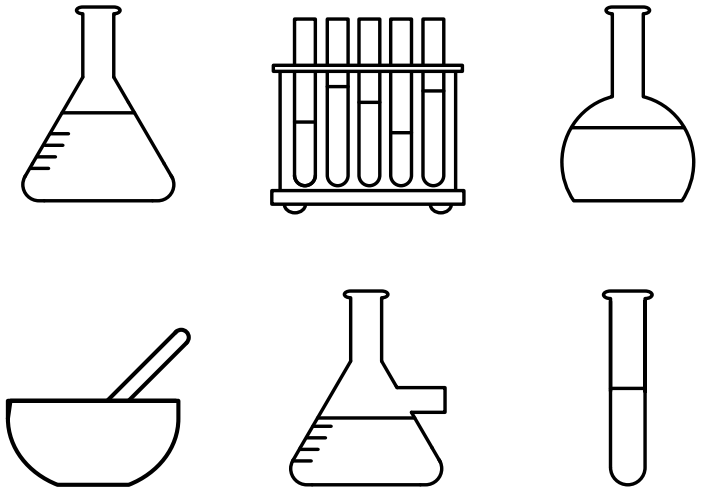
Field guide to monitor irrigation water quality in Lebanon



Field guide to monitor irrigation water quality in Lebanon

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Foreword

Water resources are under tremendous pressure due to growing demand, climate change and anthropogenic pollution in Lebanon. Rapidly declining water quality is a key indicator of the water resource degradation that characterizes now both the freshwater and marine environment across the country.

Lebanon, particularly north Lebanon is dominated by a mosaic landscape consisting of fragmented farm plots, rugged terrain and encroaching urban areas. This high-degree heterogeneity makes natural resource management even more complex, and the lack of effective enforcement mechanism of environment protection further aggravates the vulnerability of water resources. Water pollution cannot be easily contained in the interdependent and adjacent waterway network in Lebanon, and it has spill-over effects on critical ecosystem functions, human health and productive assets. The vicious cycle of pollution-degradation-remediation must be resolved to avoid further damages and irreversible consequences.

Water resource monitoring, namely water quality monitoring is an essential process to enable the prevention of water resource degradation. Monitoring is the first and foremost for establishing grounds for informed decision-making. Evidence-based strategy to address water quality issues has a wide range of benefits to all stakeholders. Good water quality improves the condition of ecosystems, thus providing healthy environment and increasing the ability to buffer climate change impacts. Regardless of whether it is drinking or non-drinking water sources, water quality has a direct impact on the living conditions of those who are in the proximity of water resources. However, neither irrigation water quality should be overlooked because it determines the overall status of natural resources and performance of agriculture sector. Better water quality has an immediate effect on agricultural productivity and quality, and hence contributes to sustainable production and food safety.

The project "Improved Water Resources Monitoring System/Integrated Water Resources Management at regional level in Lebanon", funded by the Swiss Government, is designed to establish a comprehensive water monitoring system in the north of Lebanon with the overall objective to strengthen the capacity of Lebanon's water institutions and improving their performance at regional level, thereby helping them address the sector challenges for sustainable use of water resources. The term "comprehensive monitoring system" refers to the integrated information generation, capturing quantity, quality and demand of agricultural water, as well as the climate parameters.

The project outcome is a timely contribution to the water sector development in Lebanon, which is now encountering a period of unprecedented difficulties, aggravated by the economic crisis.

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Abbreviations and acronyms

AAS	Atomic absorption spectrophotometer
BOD	Biochemical oxygen demand
CFU	Colony-forming unit
COD	Chemical oxygen demand
EDTA	Ethylenediaminetetraacetate acid
FAO	Food and Agriculture Organization of the United Nations
FAS	Ammonium iron (II) sulfate
GLP	Good laboratory practice
ILO	International Labour Organization
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
RSC	Residual sodium carbonate
SAR	Sodium adsorption ratio
SOP	Standard operating procedure
UNDP	United Nations Development Programme
UNHCR	United Nations High Commissioner for Refugees
WHO	World Health Organization

Units

°C	degree Celsius
µg	microgram
µg/ml	microgram per millilitre
µS/cm	microsiemens per centimetre
dS/cm	decisiemens per metre
g	gram
h	hour
HU	hazen units
JTU	jackson turbidity units
m	metre
l	litre
m^3	cubic metre
M	molarity
meq/l	milliequivalent per litre
mg/l	milligram per litre
ml	millilitre
mm	millimetre
mS/cm	milliSiemens per centimetre
NFU	nephelometric formazine units
nm	nanometre
NTU	nephelometric turbidity unit
pH	pH units
ppm	parts per million
rpm	revolutions per minute

Elements & chemical formulae

$AgNO_3$	Silver nitrate
As	Arsenic
B	Boron
$BaCl_2$	Barium chloride
$BaSO_4$	Barium sulfate
Ca^{2+}	Calcium ion
$CaCl_2$	Calcium chloride
$CaCO_3$	Calcium carbonate
Cd	Cadmium
CH_3COOH	Acetic acid
Cl^-	Chloride
Co	Cobalt
CO_2	Carbon dioxide
CO_3^{2-}	Carbonate ion
Cr	Chromium
Cr^{3+}	Chromium (III) oxide
Cr^{6+}	Hexavalent chromium
Cu	Copper
Fe	Iron
Fe^{2+}	Ferrous
Fe^{3+}	Ferric
H_2SO_4	Sulphuric acid
H_3PO_4	Phosphoric acid
HCO_3^-	Bicarbonate
Hg	Mercury
K^+	Potassium ion
$K_2Cr_2O_7$	Potassium dichromate
KCl	Potassium chloride
KH_2PO_4	Monopotassium phosphate
KOH	Potassium hydroxide
Mg^{2+}	Magnesium ion
$MgCO_3$	Magnesium carbonate
Mn	Manganese
Mo	Molybdenum
Na^+	Sodium ion
$Na_2B_4O_7 \cdot 10H_2O$	Borax
NH^{4+}	Ammonium
$(NH_4)_2Fe\ (SO_4)_2 \cdot 6H_2O$	Ammonium iron (II) sulfate
$(NH_4)_2SO_4$	Ammonium sulfate
NaOH	Sodium hydroxide
$Na_2S_2O_3$	Sodium thiosulfate
Ni	Nickel
NO_3^-	Nitrate ion
NO_3-N	Nitrate-nitrogen
P	Phosphorus
Pb	Lead
Pt-Co	Platinum – cobalt
Se	Selenium
SO_4^{2-}	Sulfate
Zn	Zinc

Introduction

Declining water quality is a critical issue in Lebanon, and increased efforts are required to reverse this trend. The main drivers of water degradation involve the long-term pressure of urbanization, the agricultural intensification and the infrastructural and institutional issues of wastewater management sector.

Despite the relatively reasonable but sharply shrinking water supply in Lebanon, the utilization of water supply faces further emerging problems such as the rapid surge in population, climate change-induced shifts in supply and demand patterns, and the escalating economic hardship that jeopardizes the operation and maintenance of the basic public infrastructure, including the irrigation sector.

When water quality is at issue, domestic water unequivocally remains the main field of concern. However, maintaining water quality is the prerequisite of good water service to all user types, and any decline in water quality provided to one sector might have a knock-on effect on other sectors. A more integrated approach that can overarch multiple sectors and provide a cross-sectoral network of information and action would be preferable to support the water resource governance.

Agriculture is the largest water user globally and increasing food demand and the impact of climate change are expected to further expand its water requirement. Given its direct and predominant role in the changes of water resources, agricultural water must be rigorously monitored, and intervention, whether restrictive or incentive, must be based on adequate information.

Agriculture provides direct or indirect employment to 24 percent of the active labour force, and it shares approximately 61 percent of the overall water use in Lebanon (Government of Lebanon, 2020). The ratio of irrigated area is high compared to the global average, as over 50 percent of the agricultural lands are equipped for irrigation (FAO, 2008).

However, water scarcity is growing at an unprecedented rate, and the currently outdated irrigation network does not provide sufficient and equal water supply to all. North Lebanon including Akkar is the glaring instance of the escalating problem. Despite its enormous agricultural potential, the environmental pollution, more specifically water resources degradation is the most significant barrier of sustainable natural resource use and adequate responses to growing food insecurity and climate change.

To understand the prevailing trends in the region, a pilot versatile water monitoring system is established. The deployed system rests on the concept of scalability through preparing the ground for sound infrastructure of irrigation water monitoring in the region.

Rigorous water monitoring proves fundamental to bringing irrigation water management in line with the functional demands and constraints of agriculture and water sectors.

The question inevitably arises: where does agriculture sit in the national water quality agenda? Agriculture both drives and bears the damages of water quality deterioration. On one hand, the leaching agrochemicals are the major pollutants of water resources. Equally worrying, the distribution and quality of surface water prompt farmers to drill wells and abstract the already overexploited groundwater resources. Groundwater use in coastal areas, for instance, poses the risk of salinity, and without information dissemination to farmers, the consequences might become self-perpetuating. On the other hand, poor water quality can lead to yield loss. If vital nutrients and salts exceed the absorbing capacity of crops and their concentration becomes toxic, significant crop damage is likely to occur. Polluted irrigation water has impact also on the food safety of fresh produces such as leafy vegetables and fruits, which are integral part of the cropping pattern in north Lebanon. Consequently, agriculture sector is at compounding risk due to water quality impairment in north Lebanon.

Despite the early recognition of the threat, limited number of recommendations on irrigation water quality are available. This guide is prepared to plug gaps and create a link between agricultural water management and water quality monitoring. It aims to support the efforts of professionals at regional level through the provision of a pilot system that can be scaled out to different regions in Lebanon.

The guide addresses fundamental questions that must be investigated while conducting water quality monitoring:

- What are the successive steps to establish a water quality monitoring system from design to implementation?
- What are the key elements of the monitoring protocol to ground the information generation in a solid and scientifically approved process?

Although water quality deterioration is evident in El-Bared watershed in north Lebanon, there had been no protocol in place prior to the project to monitor its water resources and provide information for further actions.

The implementation of the project activity evolved through the following steps:

1. the situational analysis to understand the root causes of water resources deterioration and establish a baseline for water quality;
2. the definition of required quality parameters and the threshold values of such parameters;
3. the identification of key monitoring sites that are representative to the area; and
4. the preparation of monitoring guidelines to facilitate the regular and consistent analysis of water quality.

Critical in establishing such a protocol is to institutionalize the process and pave the way for a continuous, robust, all-encompassing, and economically viable monitoring.

This guide builds on the acquired knowledge and experiences accumulated throughout the implementation of the project in north Lebanon, with the objective to:

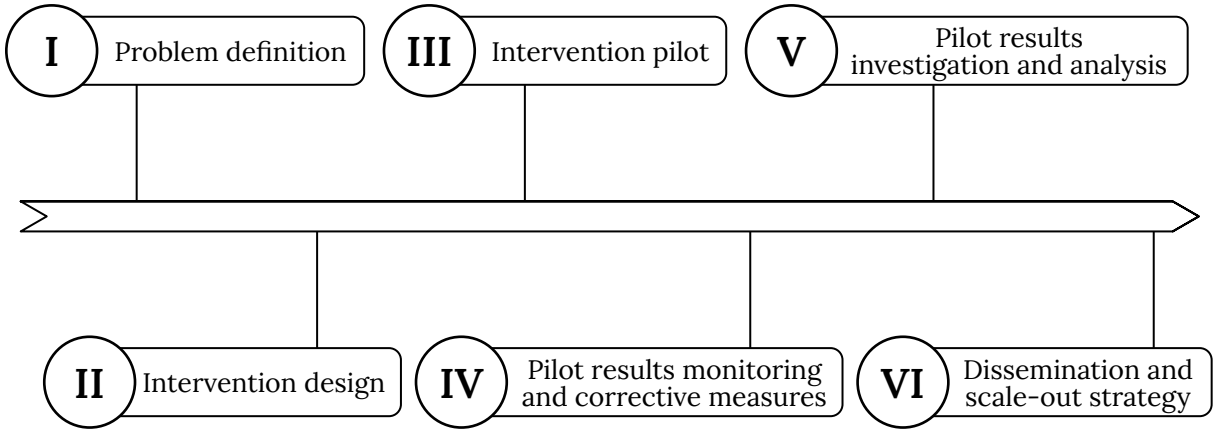
- provide a rapid overview of the steps to design a water quality monitoring system;
- give recommendations on the quality parameters and their acceptable threshold values in the context of irrigation and agricultural production;
- set out a step-wise procedure for water quality monitoring from sampling to result interpretation; and
- demonstrate the implementation with case studies.

It follows the process of evidence-based knowledge generation from the definition of problem to the scale-out of acquired information.

The guide starts with the contextualization of water quality monitoring in north Lebanon through the introduction of the command area and stocktaking of the external forces that put pressure on water resources. It then provides a protocol for sampling techniques and the required equipment. A general guidance on laboratory safety measures and quality control is crafted to ensure that the monitoring results rest upon robust laboratory datasets. Finally, the guide gives a stepwise analysis of protocol of the recommended quality parameters.

The guide is intended to be used in line with national standards and legislations. However, it substitutes neither the training requirement of the laboratory staff nor the professional experience. Its target group is national – and can be extended to international professionals – specialized in chemical engineering, water management, water policy, agricultural engineering or other relevant field of science.

Figure 1. Knowledge generation process



Source: authors' own elaboration.

1. Water resources outlook

1.1 Socio-economic characteristics of the command area

Lebanon experienced an unanticipated population growth over the recent years, which exert an enormous pressure on natural resources. Over 6.8 million people reside in the country (World Bank, 2019; UN, 2019). The uncertainty in future population vulnerability and exposure is exponentially growing, and amongst them, communities with pre-existing vulnerability are the most threatened by compounded crises.

Lebanon is ranked globally at the first place of the largest number of refugees per capita, as the Syrian crisis resulted a massive influx (UNHCR, 2019). Lebanon is also the host of Palestinian refugees, in addition, some other refugees of Iraqi, Sudanese and others live in Lebanon. Such social trend adds to the difficulties of the host countries, as public service and infrastructure are not prepared to serve the sudden increase of users.

North Lebanon is one of the most deprived areas of the country. Out of 1.16 million population, 530 000 live in poverty, including deprived Lebanese, Syrian refugees and Palestine refugees (OCHA, 2018). Agriculture is the typical employee-absorber sector in north Lebanon. Until now, the competition for agricultural works between Lebanese and non-Lebanese population had not become an acute problem, and agriculture sector had provided a relatively safe occupation for deprived families (Turkmani and Hamade, 2020).

However, situation has changed recently and provoked serious strains amongst Lebanese and non-Lebanese workers. There is a looming fear of a profound conflict amongst the multiplying jobseekers. The performance of agriculture sector is a fundamental prerequisite of avoiding further conflicts, improve food security and provide mainstay to the most vulnerable in the region, who are already prone to the lack of basic services.

In Akkar alone, over 42 000 Syrian refugees live in informal tented settlements without any access to basic infrastructure, such as safe water and sanitation services. Although Palestinian camps in Nahr El-Bared include semi-constructed housing facilities, waste disposal, water and electricity supply are irregular.

It is estimated that the overwhelming share of the vulnerable households have no clear understanding of clean water, and only 9 percent treat water before using it (UNICEF, 2012). The villagers and families living in collective shelters are in the worst situation, as they often have no access to municipal water supply and are forced to rely on intermittent water trucking system. They have no prior information on the water treatment facilities and connection to sewage system.

The overall exposure of the population to poor public services and fragile infrastructure is high,

and the current downward spiral of the political situation and economy hits the most vulnerable. The status of natural resources has paramount importance to reduce the exposure of the most vulnerable. Amongst all, access to safe water is a pre-requisite of mitigating the risks to health.

Figure 2. Informal settlement with septic tank

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The economy of Lebanon has been enduring a severe and compounded crisis. The all-time high economic contraction in 2020-2021 was the consequence of a cascade of adverse events and protracted socio-economic and political crises. Inflation in the food and beverages has been a key driver of the overall inflation, and over 41 percent of households face challenges to access food and meet basic needs (World Bank, 2021a; WFP, 2021). More than half of the population fell under the upper income poverty line, inducing an accelerated impoverishment and marginalization.

Prior to this severe crisis, the economy was stuck in a vicious cycle of volatility, reliance on remittances and unconducive business environment. The productive sectors were underfinanced, resulting in no incremental wealth generation (Government of Lebanon, 2017). While the three productive sectors of manufacturing, agriculture and tourism contribute only by 16 percent to the gross domestic product (GDP), they together employ the 26 percent of the formal labour force.

Agriculture is characterized by low productivity and quality, limited modernization, poor efficiency, and large share of informal employment that accounts for the 92 percent of the total agricultural employment. One of the main constraints of the national economy is the dilapidated infrastructure, including the water sector. Despite the good network coverage, the water service is disrupted, and wastewater treatment is limited. Water sector is the unwitting victim of the compounded crisis, as Water Establishments (WEs) accounted a considerable drop in collected revenues, and COVID-19 forced the Water Establishments to suspend the invoicing (World Bank, 2020).

Even without the current crisis, water sector, in particular irrigation and water treatment infrastructure, has been sustained through a patchy approach that focused on the most urgent corrective works instead of the prevention of condition deterioration and timely maintenance. North Lebanon is no exception.

The economic crisis has swept through all sectors, including agriculture and water sectors, and further deprived the competitiveness of agriculture, particularly on the international markets. Farmers in north Lebanon are, moreover, put in an economic disadvantage by the dual market distortion. From demand side, the uncontrolled flow of cheap agricultural imports from Syria outcompetes the local smallholders and encroaches on the accessible markets. From supply side, the hyperinflation and the significant difference in the currency exchange rate between the official and black-market offices make agricultural input prices unaffordable.

However, the role of agriculture is more vital than ever, as smallholders have strategic importance in securing household food security and employing local workforce. Provision of necessary irrigation services is the backbone to increase the agricultural

Figure 3. Seedlings before transplanting

© FAO/Eva Pek

productivity, thus contributing to the overall performance.

Nevertheless, the financial sustainability of irrigation infrastructure depends entirely on the contribution of farmers. Diminishing agricultural profitability leads to the detriment of water service quality and infrastructure, including the inevitable consequence of water resource degradation.

Despite the high agriculture potential of the country, Lebanon depends on food import, and 50 percent of the daily calories consumed come from import. Around 50 percent of the cultivated land is occupied by olives, wheat, potato and barley, nevertheless, these crops account only for 25 percent of the production value.

Moreover, export markets are constrained by the lack of certified, high-quality products. Lebanon has a dualistic farming system, consisting of commercial and small, semi-substance farms. Transforming the small farms to more productive and efficient entities with sufficient bargaining power is a common interest.

Compared to the global average, the irrigation network is expanded, and around half of the agricultural lands are irrigated. Water scarcity has been an emerging concern for a long time, but the climate change impacts, and growing population now further aggravate the situation.

The major bottlenecks hampering the agricultural development are the low water use efficiency, inefficient irrigation systems and the water pollution (Salman *et al.*, 2021). North Lebanon is characterized by large heterogeneity in both terms of production condition and production structure. Unlike the other agricultural areas, citrus, fruit trees, vegetables and limited area of open field crops are the most frequent crops, of which vegetables grown in greenhouses have been gaining ground.

Although irrigation is the cornerstone of cropping, water network becomes an involuntary source of natural resource degradation, and without exerting stronger control over irrigation water use, the irrigation network remains a sore point of the agricultural development and the condition of natural resources.

Figure 4. Greenhouse production in Akkar

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1.2 Agricultural water management in the project area

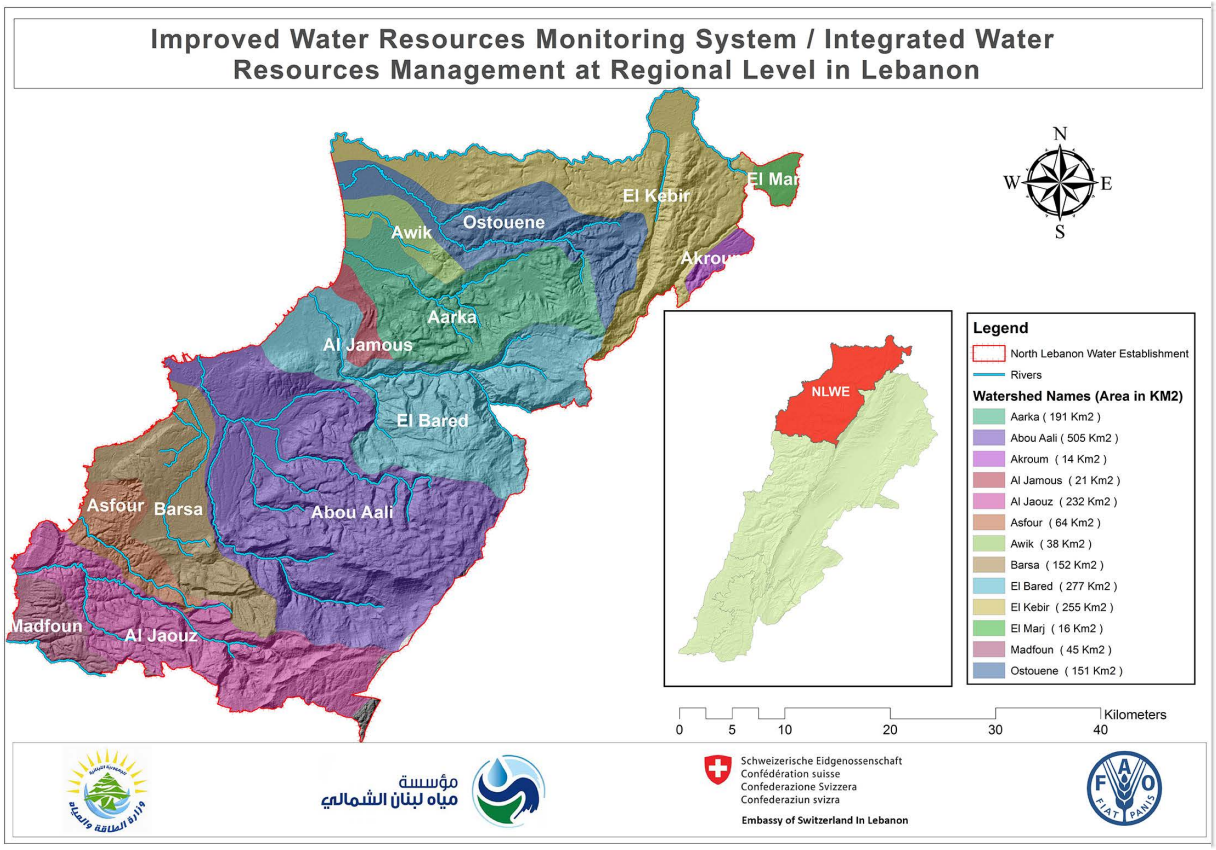
Nahr El-Bared with its 277 km^2 catchment area is the second largest of the 13 watersheds in north Lebanon. El-Bared River is around 24 km long and is sourced by several springs.

Two reservoirs are constructed in the downstream stretch, serving hydropower generation and water control purposes. The released water from the more downstream El-Bared dam is diverted to two major irrigation schemes at the right and left side, and the remaining river stream passes through the area and reaches the Mediterranean. A large volatility of river discharge is observed during a typical year, ranging from around 1 million m^3 in October to 24 million m^3 (FAO, 2021).

The peri-urban irrigation schemes in Akkar and El-Minieh are supplied by El-Bared River through gravity-fed canals. The main canals are operated at the average discharge of 900 l/s in peak irrigation seasons and convey water from the dam through multiple villages towards the Mediterranean Sea. The open-canal system consists of a main canal and a complex lower-level canal network in Akkar irrigation scheme.

El-Minieh irrigation scheme has a slightly different configuration with three parallel branches of the main canal. The lower-level canals are disrupted and cut by urban infrastructure. Many parts are wholly or partly beneath the ground surface and cross the storm water drains before running into the sea.

Figure 5. Watersheds in north Lebanon

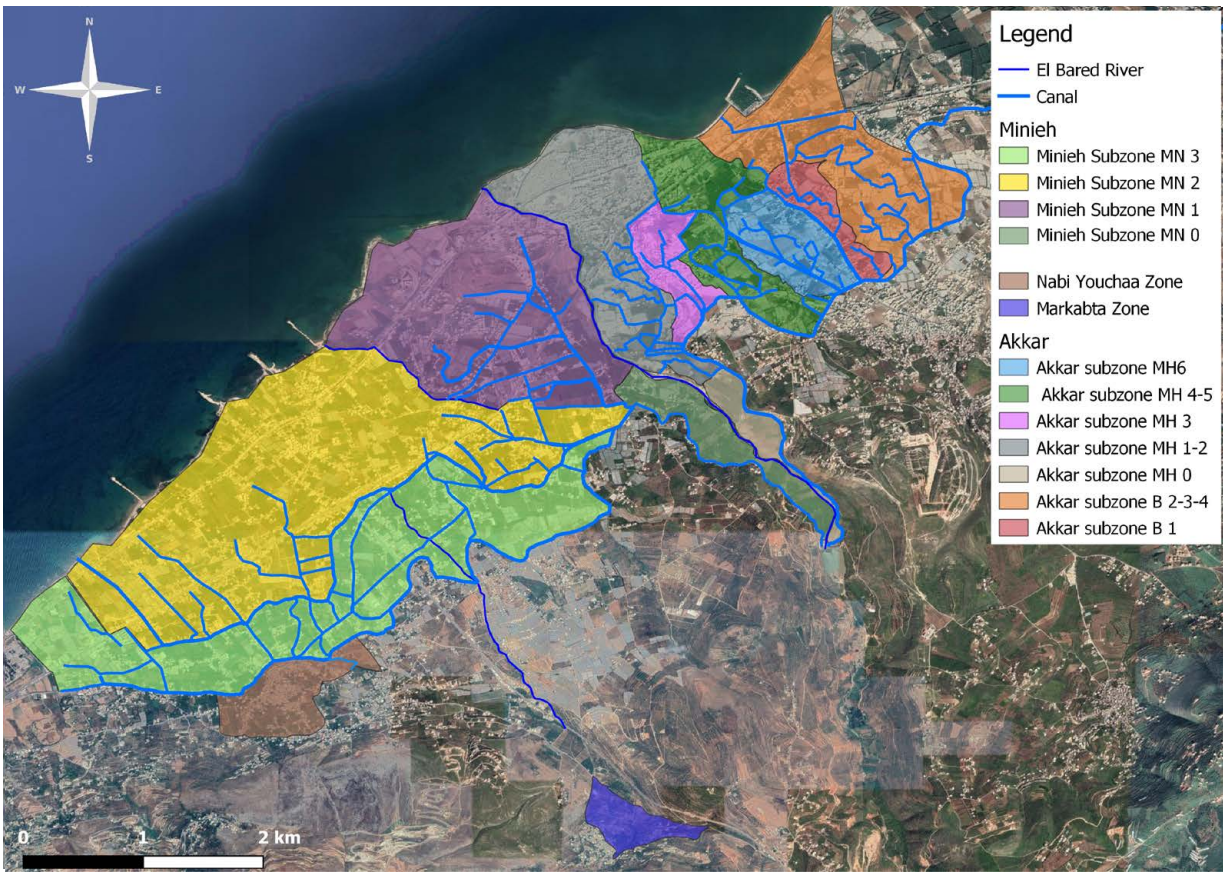


Source: authors' own elaboration.

Despite the acceptable conveyance efficiency at the headworks, the downstream stretches, and consequently the irrigated areas are of poor condition. These circumstances crowed the downstream irrigators out of the water service and prompted farmers to use groundwater as alternative water source.

Consequently, the area is characterized by mushrooming private wells that are often unlicensed and uncontrolled. Groundwater-based irrigation in the coastal area is a threat to the environment and land resources due to the suspected seawater intrusion and the salinity of the aquifers.

Figure 6. Canal network in Akkar and El-Minieh schemes



Source: Google Earth Pro v7.3.3.7786 (2020). Lebanon. 34°29'30 N, 35°58'33 E, elevation 40 m modified to comply with UN. 2020. Map of Lebanon, 4282 United Nations January 2010. https://www.un.org/Depts/Cartographic/map/profile/lebanon.pdf

1.3 Driving forces of water quality deterioration

Water quality deterioration is high on the national agenda, and in many cases, impacts are not mitigated or contained.

The water network is exposed to several pollution sources, from the feeding springs to the canal outlets to the Mediterranean, and it is barely possible to take account of all sources that affect the water resources. The sources might differ across regions, but clear understanding of the nature of pollution hotspots can suggest the most powerful measures to avoid consequences. There are well-identified driving forces that directly influence water quality, namely the issues of solid waste management and wastewater management, the interference of agriculture with water resources, and the climate change impacts.

Figure 7. Irrigation canal in villages

© FAO/Eva Pek

Due to the increasing urbanization in El-Bared watershed and the peri-urban nature of the irrigation network, the water network is directly surrounded by houses, thus creating a direct interaction between the inhabitants and water resources. Water resources are impacted by the performance of two environmentally critical sectors, namely the solid waste management and the wastewater management.

Facilities in north Lebanon have been facing stern challenges, as open dumps and landfills operate beyond their capacity, and even the timely rehabilitation works, or complete suspension are neglected (World Bank, 2011). Such dump sites are operated, by default, based on scarce resources, as the fee collection efficiency is low, and the municipal budgets are insufficient to cover the operation and maintenance costs. This, in turn, results in a poor and erratic garbage collection service that forces households to pile and individually dispose waste. Communities routinely use waterways, including irrigation networks for solid waste transport.

Another considerable issue is the poor sewage network coverage, stemming from the lack of infrastructure and weak cost recovery prospects. The combined capacity of the five larger treatment plants and the small-scale plants in the country is estimated at 47 million m^3, equivalent to less than 20 percent of the total generated domestic sewage (UNDP and ILO, 2011). One of the major treatment plants is constructed in Tripoli in north Lebanon, and several secondary treatment facilities are planned in the area. Considerable efforts have been taken to increase the national capacity and the rate of connection to treatment plants. However, capital investment is only one side of the equation. The financial sustainability grounded in the contribution of users is of prime concern. A long-term functionality of treatment plants cannot be projected without reviving the faith of communities in public services.

North Lebanon has as low as 44.7 percent rate of connection to wastewater treatment plants, and most of the connected households are located around Tripoli. Mountain villages and distant areas are not likely to have direct connection to either major or secondary facilities, moreover, the existing infrastructure is already outdated. Households without connections rely on septic tanks, cesspools and individually manufactured sewage outlets. The houses around waterways dump raw sewage directly into the flow. These alternative practices are the main causes of nonpoint source pollution and have a cascading effect on both the environment and the human health. The measured biological contamination is the direct impact of this interference and lack of harmonization amongst sector development.

Figure 8. Accumulated solid waste in the irrigation canal in north Lebanon

© FAO/Eva Pek

Agriculture adds to the potential threat of pollution. Controlling the side-effects of small-scale production is difficult due to the scattered, mosaic-type of agricultural landscape. The applied fertilizer and pesticide use vastly exceeds the recommended amount, and leaching agrochemicals pollute both the groundwater, surface water and soil resources. Another less visible but equally detrimental impact of agriculture is the over-abstraction of groundwater for irrigation purposes.

The accessibility of surface water resources is often poor due the deteriorated infrastructure and heavily polluted surface water bodies. Downstream farmers are forced to tap on groundwater sources

Figure 9. Disposed garbarge in orchards

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Box 1. UN Water: compendium of water quality regulatory frameworks: which water for which use?

The UN Water released the *Compendium of water quality regulator frameworks in support of guidelines for managing water quality globally*. Beyond the numerous recommendations and rich body of case studies, the Compendium lines up the main criteria for assessment to enable effective water quality instruments. The set of criteria proposes the following questions to determine the effectiveness of instruments:

- Are the objectives sufficiently clear so that they can be monitored through a set of indicators?
- Are there monitoring and evaluation schedules?
- Is there laboratory analytical capacity and quality control, ensured by having analyses conducted by an accredited laboratory?
- Is there a baseline against which future situations can be assessed or should be established?
- Is there access to information about the facilities that have permits to discharge pollutants?
- Is there a regulatory framework that enables public acceptance of the respective water quality requirements?

The current guide responds to the criterion related to laboratory analytical capacity and quality control by equipping practitioners with knowledge and skills on analysis methods, and hence strengthen decision-making with robust results. The guide also contributes to the global endeavour to sustainably manage and conserve water resources (UN Water, 2015).

at any cost to overcome water shortage. Wells constructed without environmental considerations and monitoring are potential sources of pollution, degradation and exploitation. Groundwater use, particularly in the coastal areas, carries the risk of decline in water table and secondary salinization. The increased salinity level of wells in the coastal areas indicate that the groundwater withdrawal already outpaces the recharge rate, thus accelerating the saltwater intrusion (World Bank, 2003).

Water bodies adjacent to agricultural and coastal areas are subjected to multiple pressure and become the interface between marine and freshwater ecosystem degradation. Climate change induces a growing water imbalance of supply and demand partly due to the changing trends in precipitation and snowmelt (World Bank, 2013). The average annual rainfall has not changed considerably, however, the rainfall pattern shows increased number and intensity of peaks. The area of dense snowfall has decreasing, as well as the average residence time of dense snow dropped from 110 to less than 90 days (Shaban, 2009).

Overall, the intensified precipitation and shrinking snowmelt periods affect the river streams, shift and extend the drought periods at lower altitudes, and induce more devastating floods. The potential changes in water cycle reduce raw water quality and the absorption capacity of natural resources (World Bank, 2021b).

In this context, the control of water quality becomes undeniably complex. Thus, the first step to respond to the crisis is the establishment of regular water quality monitoring in the area. The monitoring system is primarily concerning the agriculture sector; however, it provides information to a wider set of stakeholders sectors.

2. A protocol for water quality analysis

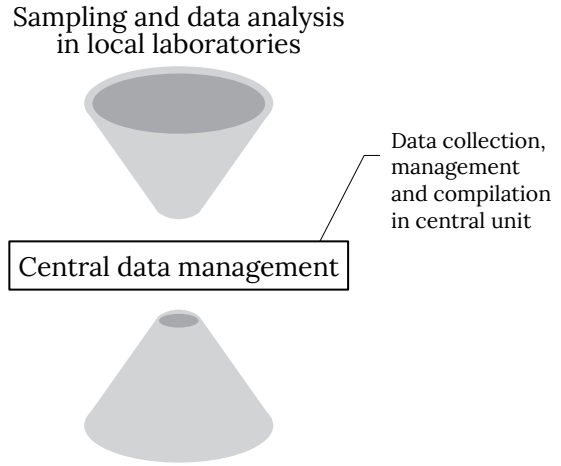
2.1 Prerequisites of water quality monitoring

The overall objective of the monitoring of irrigation water resources is to support farmers in accessing safe and good quality water for irrigation purposes, while mitigating and eliminating the environmental and social risk of quality deterioration.

The sustainable and integrated system of water quality monitoring, however, requires the stocktaking of technological feasibility, economic, interdisciplinary and environmental considerations. The considerations are the general expectations that should be taken into account during the design of water monitoring systems:

1. Water quality monitoring has several equipment and technology prerequisites, without which the implementation is not feasible. Therefore, the very first step of designing such systems is the appraisal of existing and required laboratory equipment and tools, means to access the sites, and available human resources.
2. Monitoring has considerable cost implications that involve both investment need and increased running cost. Water monitoring equipment requires maintenance and skilled operators who are requested to allot time for sampling and analysis. Adding to the running costs, a continuous supply of reagents must be ensured to prepare scheduled or ad hoc analysis. Streamlining the water quality protocol to the most reasonable sample size and frequency contributes to the financial sustainability of regular monitoring.
3. Water quality monitoring has secondary benefits, as some results can be interpreted in different context to agricultural water management. This is of utmost importance when irrigation system is located nearby or within urbanized areas. Water pollution has critical impacts on all, including health of people, environment and productive assets. While defining the protocol of monitoring, the secondary benefits must be accounted and information sharing mechanism must be set up to strengthen its interdisciplinary nature.
4. Any changes in measured water quality parameters have direct impact on the surrounding ecosystem, including the productive natural resources. Analysis of water quality data must be framed into the context of the environment and interconnectedness of waterways and natural resources.

Figure 10. Data management design of water quality monitoring



Source: authors' own elaboration.

The design of water quality monitoring is expected to include data-sharing and publication outlets. Isolated data collection and analysis might lead to the loss of critical information and prevent the identification of cause-effect relationships.

To overcome these challenges, glass-hour design is desirable while planning a monitoring system. Such structure involves decentralized sampling and analysis, centralized data collection and synthetization, and information sharing with key stakeholders.

Many of the pre-considerations can be tackled by proper site selection. Although the sites can evolve by the changing conditions, the location has a profound importance to draw adequate conclusions.

2.2 Site selection criteria

Site selection determines the robustness and explanatory power of water quality analysis. The site selection is the subject of strategic decisions and technical recommendations.

It is important to investigate how strategic criteria influence the final selection of key monitoring points. Water quality monitoring capturing too large areas might over-generalize the analysis results and fail to obtain crucial information about the sources and effects of changes in water quality. On the other side, overly confined approaches would put unnecessary burden on implementing authorities in terms of human resources and budget and result in redundancy.

Site selection must also be in line with the overall objective of the monitoring, e.g. agricultural water management. To acquire a realistic understanding of the prevailing trends and ensure data consistency, one approach is to align the monitoring system to hydrological boundaries, while also considering the within-system equipment appropriate to contain the pollution. Hydrological and administrative boundaries are, however, often distinct, and despite the shared water sources, water management falls under different administrative units and authorities. Accordingly, monitoring network may span across different authorities, and effective coordination must be ensured to operate the system. Introduction of agreed and commonly adopted protocols of sampling and analysis is important to set up consistent datasets and data history. Therefore, the site selection must embrace a participatory approach, where stakeholders can reach common understanding and engage in the implementation and operation.

It is well-understood that random and one-point measurement is not always sufficient and straightforward, because it might be distorted by localized causes. On this basis, the integrated and network-like implementation of water quality monitoring is more appropriate to overcome these challenges. Simultaneous measurements at multiple points lead to a more comprehensive situation analysis and allows the data comparison and cross-validation. Monitoring network is recommended in public and open irrigation systems that are prone to stresses by different factors.

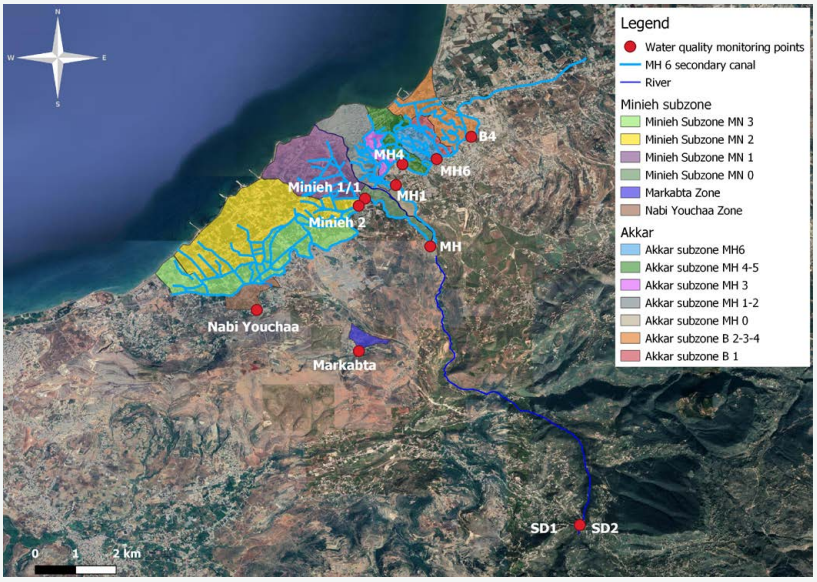
Box 2. Case study: multi-criteria system of site selection in north Lebanon

The project crafted and tested a multi-criteria system of site selection. The iterative process of selection finalization resulted in a set of key criteria:

- cover the entire area, from source to fields;
- define the proximity of potential point source and diffuse pollution;
- estimate the cascading effect of contamination along the network and assess the water control equipment;
- consider the risk of contamination to agricultural production and other stakeholders;
- provide accessibility for sampling;
- involve the key stakeholders responsible for implementation;
- optimize the number of sites according to the density of pollution sources; and
- ensure integration with other monitoring systems (i.e. discharge, weather or water use).

Guided by this multi-criteria system, the implementation of quality monitoring system is phased into two successive steps. The first water monitoring design responded to six of the presented criteria, thus defining fifteen monitoring sites. The results of the analysis enabled a streamlined and rationalized number of key monitoring sites to reach a limited number of sites suitable for regular monitoring and optimized resource requirement (Figure 11). The current monitoring system provides a source-to-sea monitoring network covering directly almost 3 000 ha.

Figure 11. Data management design of water quality monitoring



Source: Google Earth Pro v7.3.3.7786 (2020). Lebanon. 34°29'30 N, 35°58'33 E, elevation 40 m modified to comply with UN. 2020. Map of Lebanon, 4282 United Nations January 2010. https://www.un.org/Depts/Cartographic/map/profile/lebanon.pdf

2.3 Collection of water samples and sampling equipment

A fundamental step of water analysis is the collection of water samples. Despite the accuracy of laboratory testing, the rightness of the analysis lays in the representativeness of the material, according to its source (dam, river, well, etc.).

The following general rules should be followed:

1. **Contamination:** contamination of water samples should be avoided during collection, handling and transport to the laboratory, as well as during the analysis procedure.
2. **Completeness:** complete records of the sampling sites, including dates, depths, names of the persons collecting the samples, numbering, etc. should be done directly in the field at the time of collection to avoid any incorrigible error.
3. **Reconnaissance trips:** making a reconnaissance visit to the sampling sites with a map is important to decide or confirm the number of sampling points and methods of collection.
4. **Workplan:** the preparation of a workplan supports the establishment of the time needed for the water sampling activities. Ideally, water samples should be returned to the laboratory within a few hours of being taken.
5. **Checklist:** the preparation of checklists is important to take or timely order all the supplies and equipment needed for the sampling and on-site testing.
6. **Understanding of equipment & calibration:** it is fundamental to know the proper use of sampling equipment and the physical and chemical limitations, as well as run a calibration test when needed (i.e. pH, EC, turbidity, etc.)
7. **Safety:** safety of personnel must never be compromised. In this regard, all personnel must be familiar with the procedure and equipment, follow safety requirement and planned sampling order; wear appropriate protective clothing, as well as clean containers and rinse equipment before sampling.
8. **Microbiological analysis:** the time between sample collection and analysis should not exceed 6 hours, while 24 hours is considered the absolute maximum. Collected samples should immediately be placed in a lightproof insulated box containing melting ice or ice packs with water to ensure rapid cooling. If ice is not available, the transportation time must not exceed 2 hours, especially during hot weather.
9. **Chlorine:** when the samples are collected from water that contains or may contain traces of chlorine, sodium thiosulfate ($Na_2S_2O¬3$) must be used to inactivate and neutralize any chlorine present in the water. If the chlorine in the water is not inactivated, it may kill the microbes during transit and erroneous results will be obtained.

Sampling methods are distinguished amongst the type of water and the rules must be respected to avoid misinterpretation of the analysis. Instructions on two sampling methods per water types are discussed in this chapter: sampling from flowing water and sampling from still water (dams, lakes, reservoirs etc.). Complementary information is provided on sampling from surface water.

2.3.1 Sampling from flowing water

The following measures are recommended in case of sampling from flowing water:

- If a stream gaging station is installed, the sample should be collected from a point close to the station and the discharge is measured at the time of sampling.
- Bridges, harbours, roads, boat ramps, and other structures should be avoided unless these structures are part of the study.
- Samples should be collected far enough above and below stream flow or point source of contamination unless these points are part of the study.
- Selection and collection should be from a few points at cross section of the river or stream where samples can be collected at any time if needed.
- Suitable sampling equipment and containers should be used:
    - » for organic compounds: fluorocarbon polymer, glass or metal;
    - » for inorganic constituents: fluorocarbon polymer, uncoloured plastic or glass (metal or rubber containers should not be used);
    - » for microbial analysis: sterilized glass, metal or fluorocarbon containers with tight and sterilized cover.

2.3.2 Sampling from still water

Water samples are usually collected at multiple locations in the water body and at multiple depths:

- Number and locations of sampling points (usually between 4-10 points, depending on the surface area of the lake) should be selected at equal intervals. The number is not picked haphazardly.
- The cross-sectional variation of the lake (pH, electrical conductivity, dissolved oxygen, temperature and turbidity) should be measured, recorded and reviewed. Based on this data, the number of sampling points across the lake can be decided.
- Samples should be collected at different depths:
    - » The sampler should be lowered at predetermined transit rate until slight contact with the lakebed.
    - » The sampler should be raised immediately at constant transit rate.
    - » The descending and ascending transit rates do not have to be equal, but each rate must be constant.
    - » Lakebed should not be disturbed by the sampler.
    - » The sampler container should not be overflowed or under-flowed.
    - » The procedure should be repeated at the remaining verticals along the cross section, covering at least three depths (surface, middle and bottom).
- Sampling time and depth should be correctly recorded as well as all field observations and deviations from the procedure.
- Containers should be rinsed with deionized water and placed in a clean plastic container.

- Non-isokinetic sampling methods are summarized below:
    - » The dip sampling method: involves dipping a narrow-mouthed bottle into water body.
    - » The discrete sampling (point): involves lowering to a specified depth and collecting a small quantity by opening then closing the sampler.
    - » The pump sampling method: suction-lift or submersible pump are mostly used to collect a point sample by lowering the submersible pump or the suction hose to a selected point. Automatic pumping used in specific situations such as when large number of samples is needed to be collected within relatively short time. This equipment is recommended for sampling the water across large lakes from a small boat.
    - » Separate clean containers should be used for the collection of sediments samples, which generally are not field-composited. Upon the arrival of the sediment sample (slurry) to the laboratory, it is filtered, and the solid part is analysed separately from the liquid part.

2.3.3 Sampling from surface water

For collecting water samples from water canals and flowing streams, the following is recommended:

- Simple immersion of clean bottle below the surface of water body is the most widely used method for collection of surface water samples. This method eliminates the need for other equipment.
- The open bottle should be immersed by hand (with gloves) into surface water and water should be allowed to slowly run into the bottle minimizing turbulence. Sediments should not be disturbed.

2.4 Equipment needed for water sampling along the river and across the lake

It is common for some laboratories to use a stick (2 m) with a plastic bottle at its end. However, the water samples collected via this piece of equipment represent only the water close to the edge of the lake or the river.

Therefore, the following equipment, in addition to a boat for crossing lakes or dams, is suggested:

- Stainless steel gauging;
- Watermark hand-operated - vacuum/pressure pump;
- Peristaltic pump;
- Nasco 6′ to 12′ extendible swing sample;
- Conbar Sub-Surface Grab II Telescopic sampler;
- Nalgene Wide-Mouth bottle 32 oz./1 l;
- Nalgene Wide-Mouth bottle 8 oz./250 ml; and
- Replacement bottle holder for swing sampler.

Figure 12. Example of Nalgene wide-mouth bottle

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Figure 13. Example of peristaltic pump

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2.5 Time elapsing between collection of samples and analysis

In general, the shorter the time elapsing between collection of samples and analysis, the more reliable the results will be.

The allowable time that may elapse between collection of water samples and beginning of analysis can be summarized in Table 1.

Table 1. Allowable time between sample's collection and analysis.

Physical and chemical analysis	**Time between collection and analysis (h)**
Groundwater	72
Fairly pure surface water	48
Polluted surface water	12
Sewage effluent	6
Raw sewage	6
Bacteriological examination	**Time between collection and analysis (h)**
Samples kept at less than 10 °C	6

2.6 General laboratory guidelines

Once the sample is properly collected, laboratory analysis must be carried out with extreme accuracy and attention. Safe working in a chemical laboratory needs special care, both in terms of design and construction of the laboratory building, and handling and use of chemicals. In fact, in chemical laboratories, the use of acids, alkalis and some hazardous and explosive chemicals is inescapable.

Moreover, some chemical reactions during the process of analysis may release toxic gases and if not handled well, may cause an explosion. Inflammable gases are also used as a fuel/heating source. Thus, for chemical operations, special chambers also need to be provided:

- **Air temperature and humidity:** since water samples and chemicals are often affected by the temperature and humidity, they must be kept at a constant level. Air temperature of laboratory and working rooms should be maintained between 20–25 °C, while humidity should be kept at about 50 percent.
- **Proper air circulation:** to avoid a long stationing of hazardous and toxic fumes and gases in the laboratory, proper air circulation should be kept. The release of gases and fumes in some analytical operations is controlled through the use of fume hoods, acidic/alkaline solutions for confinement or flowing water for washing. Maintenance of clean and hygienic environment in the laboratory is essential for the good health and safety of the workers.
- **Storage:** caution is required to store acids and hazardous chemicals in separate and safe racks.
- **Inventory:** an inventory of all the equipment, chemicals, glassware and miscellaneous items in a laboratory should be maintained.
- **Building:** a safe laboratory building should have suitable separate rooms for different purposes and for performing different operations.

2.7 Laboratory safety measures

The safety of staff, both in the field and in the laboratory, is of greatest importance. All staff should be trained on safety procedures relevant to their work, such as the use of first aid kits, which are kept in handy at a conspicuous working place in the laboratory.

All laboratories should have a safety policy that should cover cleaning, disinfection and the containment of hazardous substances, which includes the following general recommendations:

- Fire extinguishers must be well maintained, filled and ready to be used, and a bucket of sand must be kept in the laboratory to be used in case of a fire burst.
- Sand can also be used to remove spilled liquids on the floor.
- All the staff should wear safety clothing, such as gloves, masks, safety glasses, laboratory over coats and shoes. In addition, they have to observe normal laboratory safety practices in connecting equipment with power supply, and only qualified personnel must do all electrical work. All the maintenance instrument manual and logbook for each equipment are required in the lab to avoid mishandling, accident and damage to equipment.

Figure 14. Equipment and reagents in the laboratory of Akkar

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Special care is required while operating equipment, handling of chemicals and waste disposal:

- **Equipment:** electrical cables, plugs and tubing need proper check to avoid accidents. Various types of gas cylinders used in the laboratory like acetylene, nitrous oxide, and liquified petroleum gas may be kept under watch and properly sealed of capped and may be stored in ventilated cupboards. Safety equipment such as fire extinguishers, eye fountains and first aid kits should be suitably located and readily available; and they should be routinely checked and all staff should be trained on their use.
- **Chemical reagents:** hazardous chemicals may be stored in plastic bottles. While working with chemicals such as perchloric acid, fume hood should be used. Chemicals may be properly labelled indicating their hazardous nature. Bottles with inflammable substances need to be stored in stainless steel containers. All the staff must wash hands after handling toxic or hazardous chemicals.
- **Waste disposal:** each country has special rules and methods for disposal of hazardous waste. Cyanides, chromates, arsenic, selenium, cobalt and molybdate are very commonly used hazardous chemicals that should never be disposed in the laboratory sink, but should be collected in a metal container for proper disposal at the specified places and in the manner as described in the country's law for waste disposal.

Box 3. Special precautions

Always bare in mind the following special precautions in a laboratory environment:

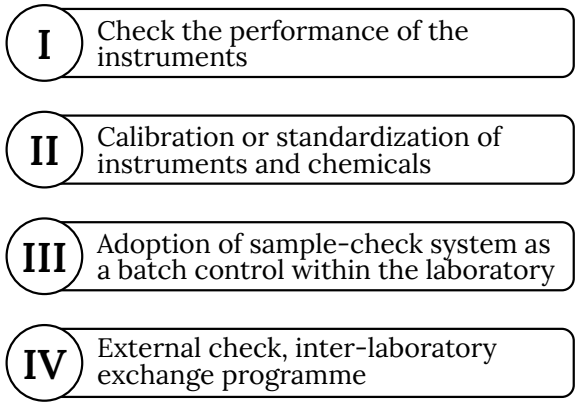
- Chemicals are never sucked by mouth when using a pipette but an automatic pipetting device is used.
- Forceps or tongs are used to remove containers from the hot plates, ovens, and furnaces.
- Laboratory glassware are not used for eating or drinking.
- Fume hood is used while handling concentrated acids, bases and hazardous chemicals.
- A centrifuge cover is never opened until the machine has stopped. New centrifuges usually have an auto-lock system.
- Acid is added to water and not water to acid while diluting the acid.
- Labels are always put on bottles, vessels and wash bottles containing reagents, solutions and water.
- Acids in fume hoods are handled and direct contact is avoided.
- Labels of the bottles are always red before opening them.

2.8 Laboratory quality control

Quality control is an important part of quality assurance, which is defined by the International Organization for Standardization (ISO) as "the operational techniques and activities that are used to satisfy quality requirements".

Quality assessment or evaluation is necessary to see if the performed activities are effective. Thus, an effective check on all the equipment activities and processes in a laboratory can only ensure that the results pronounced on a water sample are within the acceptable parameters of accuracy. In quality control system, the following steps are involved to ensure that the results delivered are acceptable and verifiable by another laboratory.

Figure 15. Steps of quality control system



Source: authors.

To ensure obtaining accurate and acceptable results of analysis on a sample, the laboratory has to run in a well-regulated manner, where the equipment is properly calibrated and the methods and techniques employed are scientifically sound, which will give reproducible results.

For ensuring the high standards of quality, good laboratory practices (GLP) have to be followed. The GLP can be defined as "the organizational process and the conditions under which laboratory studies are planned, performed, monitored, recorded and reported". Thus, the GLP expects a laboratory to work according to a system of procedures and protocols whereas the procedures are also specified as the standard operating procedure (SOP). The purpose of a SOP is to carry out the operation correctly and always in the same manner. It should be available at the place where the work is done. If, for justifiable reasons, any deviation is allowed from SOP, the deviated procedure should be fully documented.

To sum up, all the operations have to be properly documented so as no chances are left for error or uncertainty. In this regard, it is necessary to define precise concepts.

2.8.1 Error

An error, if not attributable to the instrument accuracy or method and observes capacities, occurs when the results of successive determination differ among themselves to a greater or lesser extent.

Many factors could be responsible for this difference, which in different cases may be small or large. Therefore, the reliability of the results depends on the magnitude of these differences, and even if the average value is accepted as most probable, this may not always be true value.

The error may be caused due to any deviation from the prescribed steps required to be taken in analysis, such as the purity of chemicals, their concentration/strength and the accuracy of the instruments and the skill of the analyst.

An error can be defined as absolute or relative. The error in absolute terms is the difference between the measured and the true value. The absolute error is a measure of the accuracy of the measurement. The accuracy of a determination may, therefore, be defined as the concordance between it and the true or most probable value. The relative error is the absolute error divided by the true value.

2.8.2 Precision and accuracy

Precision is defined as the concordance of a series of measurements of the same quantity. The mean deviation or the relative mean deviation is a measure of precision. In quantitative analysis, the precision of a measurement rarely exceeds 0.1 to 0.2 percent.

Accuracy expresses the correctness of a measurement, while precision expresses the reproducibility of a measurement.

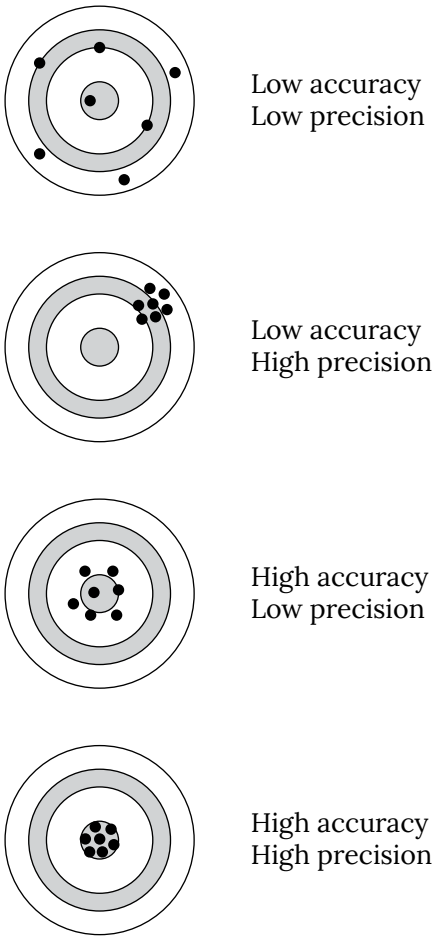
Precision always accompanies accuracy, but a high degree of precision does not imply accuracy. In ensuring high accuracy in analysis, the cleanliness of the used glassware and laboratory spaces in addition to accurate preparation of reagents including their perfect standardization is critical.

For all estimation, where actual measurement of a constituent of the sample in terms of the "precipitate formation" or formation of "coloured compound" or "concentration in the solvent" is a part of steps in estimation, chemical reagents involved in such aspects must always be of high purity, which is referred as AR-grade (analytical reagent).

2.8.3 Detection limit

The analysis for trace elements in water need arises to measure very low contents of analytes. Modern equipment is capable of such estimation. However, while selecting an equipment and the testing method for such purpose, it is important to have information about the lowest limits up to which analytes can be detected or determined with sufficient confidence. Such limits are called detection limits or lower limits of detection. The capacity of the equipment and the method may allow to detect the traces of analyte in the sample. In quantitative terms, the lowest contents of such analyte may be decided through appropriate testing in the laboratory, and the service laboratories are generally provided with such limits.

Figure 16. Precision vs accuracy



Source: authors' own elaboration.

Figure 17. On-job training on equipment use in involved laboratories

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2.9 Quality control of analytical procedures

2.9.1 Independent standards

The ultimate aim of the quality control measures is to ensure the production of analytical data with a minimum of error and with consistency.

Once an appropriate method is selected, its execution must be done with utmost care. To check and verify the accuracy of analysis, independent standards are used in the system (internal standards). The extent of deviation of analytical value on a standard sample indicates the accuracy of the analysis.

Independent standards can be prepared in the laboratory from pure chemicals. When new standard is prepared, the remainder of the old ones always has to be measured as a mutual check. If the results are not within the acceptable levels of accuracy, the process of calibration, preparation of standard curve and the preparation of reagents may be repeated until acceptable results are obtained on the standard sample. After assuring this, analysis on an unknown sample can be started.

Apart from independent standard, certified reference samples can also be used as 'standard'. Such samples are obtained from other selected laboratories where the analysis on a prepared standard is carried out by more than one laboratory and such samples along with the accompanied analytical values are used as a check to ensure the accuracy of analysis.

2.9.2 Use of blank

A blank determination is an analysis without a sample by going through all steps of the procedure with the reagents only. The use of a blank accounts for any contamination in the chemicals used in actual analysis. The 'estimate' of the blank is subtracted from the estimates of the samples.

The use of 'sequence control' samples is made in long batches in automated analysis. Generally, two samples, one with a low content of analyte and another with high content of known analyte (but the contents falling within the working range of the method) are used as standards to monitor the accuracy of analysis.

2.9.3 Blind sample

A blind sample is a sample with known content of analytes. It is inserted by the head of the laboratory in batches and at times unknown to the analyst to determine the accuracy of the analysis.

Various types of sample material may serve as blind samples such as control samples or sufficiently large leftover of test samples (analysed several times).

2.9.4 Validation of procedures of analysis

Validation is the process of determining the performance characteristics of a method or procedure. It is a pre-requisite for judgement of the suitability of produced analytical data for the intended use. This implies that a method may be valid in one situation and invalid in another.

If a method is very precise and accurate but expensive for adoption, it may be used only when the data with that order of precision are needed. The data may be inadequate if the method is less accurate than required. Two types of validation can be followed, as explained in Box 4 and Box 5.

If an error is suspected in the procedure and uncertainty cannot readily be solved, it is common to have the sample analysed in another laboratory of the same system/organization. The results of the other laboratory may or may not be biased, hence doubt may persist.

Box 4. Validation of own procedure

In-house validation of method or procedure by individual user laboratory is a common practice. Many laboratories use their own version of even well-established method for reasons of efficiency, cost and convenience. A change in dilution factor, extraction temperature, etc. results in changed values, hence needs validation. Such changes are often introduced to consider local conditions, cost of analysis, required accuracy and efficiency. Validation of such changes is the part of quality control in the laboratory. Most service laboratories may not be able to modify the standard method. Therefore, they should follow the given method as accepted and practiced by other laboratories.

In addition to method validation, a system of internal quality control is required to be followed by the laboratories to ensure that they are capable of producing reliable analytical data with minimum error. This requires continuous monitoring of the operation and systematic day to day checking of the produced data to decide whether these are reliable enough to be released.

Following steps need to be taken for internal quality control:

- A blank and a control (standard) sample of known composition should be used along with the samples under analysis.
- The analytical values should be rounded off to the second decimal place. The value of third decimal place may be omitted if less than 5. If it is more than 5, the value of second decimal may be raised by 1.
- Since the quality control systems rely heavily on control samples, the sample preparation may be done with great care to ensure that the sample is homogenous; sample material is stable and stored properly in the laboratory; relevant information such as properties of the sample and its origin. The samples under analysis may also be processed or prepared and stored similar way to that of the standard (control) sample. As and when an error is noticed in the analysis through internal check, corrective measures should be taken. The error can be due to calculation or typing. If not, it requires thorough check on sample identification, standards, chemicals, pipettes, dispensers, glassware, calibration procedure and equipment. The standard may be old or wrongly prepared. Pipette may indicate wrong volume; glassware may not be properly cleaned and the equipment may be defective or the sample intake tube may be clogged in case of flame photometer or atomic absorption spectrophotometer. Source of error may be detected and samples should be analysed again.

The sample check by another accredited laboratory may be necessary and useful to resolve the problem. An accredited laboratory should participate at least in one inter-laboratory exchange program. Such programs do exist regionally, nationally and internationally for method performance studies and laboratory performance evaluations.

In such exchange programs, some laboratories or organizations have devised the system, where periodically samples of known composition are sent to the participating laboratory without disclosing the results. The participating laboratory will analyse the sample by a given method and find out the results. It provides a possibility for assessing the accuracy of the method being used by a laboratory and the adoption method suggested by the lead laboratory.

Box 5. Validation of the standard procedure

This refers to the validation of new or existing methods and procedures intended to be used in many laboratories, including procedures accepted by national systems or ISO. This involves an inter-laboratory programme of testing the method by a member of selected renowned laboratories according to a protocol issued to all participants. Validation is not only relevant when non-standard procedures are used, but just as well when validated standard procedures are used and even more so when variants of standard procedures are introduced. The results of validation tests should be recorded in a validation report from which the suitability of a method for a certain purpose can be deduced.

3. Parameters of irrigation water quality

Water quality has direct impact on food safety and agricultural productivity, so consistent monitoring is recommended even in areas with less stressors. For example, if agricultural lands are exposed to salinization, frequent monitoring of electrical conductivity is required to mitigate the risk. Or, if industrial or urban waste management is not well organized, biological analysis must be regularly conducted, and safety measures for irrigators and food safety measures for leafy vegetables must be introduced.

This chapter introduces the recommended parameters to monitoring physical, chemical and biological properties and provides an analysis protocol for each parameter. The chapter also provides recommendations on the interpretation of irrigation water quality by setting threshold values for each parameter.

3.1 Physical analysis

The physical properties of water are related to the appearance of water: turbidity, temperature, colour, taste, and odour.

3.1.1 Turbidity

Turbidity is the amount of cloudiness in the water caused mud, chemical precipitation or some microorganism growth. During rainy seasons, when mud and silt are washed into rivers, streams, and canals, high turbidity can block filters, fill pipes with deposits, and also damage valves.

The typical instrument used to measure turbidity is the nephelometric turbidity meter that measures the intensity of light diffused at an angle of 90° in relation to the incident light. The apparatus' readout unit is expressed in nephelometric formazine units (NFU). There are many different types of turbidity meters available. Usually, they are accurate in measuring low turbidity. It is recommended to follow the procedure provided by the manufacturer's instructions. Turbidity is also measured in nephelometric turbidity unit (NTU) or Jackson turbidity unit (JTU). The two units are roughly equal. The NTU is the most commonly used unit.

3.1.2 Temperature

The temperature influences the rates of chemical and biological processes and affects the amount

of dissolved oxygen. As temperature increases, dissolved oxygen (DO) decreases in water.

The water temperature is expressed in degrees Celsius or Fahrenheit using thermometers with resolutions of 0.1 °C and accuracy ±1 °C. The following method should be followed to measure temperature:

- The thermometer should be submerged two-thirds below the water surface.
- Measurement should be taken in a central flowing location.
- The thermometer should be adjusted to the water temperature at least 1 minute before removing it from the water and quickly take the temperature reading and record it or take the reading while the thermometer is still immersed in the water.

3.1.3 Colour

Most of the colour in water comes from suspended materials and algae. Highly coloured water has significant effect on aquatic plants and algae because it limits the penetration of light and the rate of dissolved oxygen in water. The colour scale used for measuring water quality is known as the platinum – cobalt scale (Pt-Co) from the American Public Health Association (APHA). It ranges from 0 Hazen units (HU), indicating clean or distilled water to 500 HU, indicating very dark polluted water.

3.1.4 Taste and odour

Taste cannot be measured, and people differ in their evaluation to taste. Clean natural water is tasteless. However, there are instruments developed to extract odour from water samples and measure the components on the principle of gas chromatography.

3.2 Chemical analysis

The standard method for measuring the chemical analysis of irrigation water is by measuring the water salinity and sodicity in the laboratory, which includes a complete analysis of major cations -sodium (Na^+), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}), and anions -carbonate (CO_3^{2-}), bicarbonate (HCO_3^{1-}), chloride (Cl^-), sulfate (SO_4^{2-}) and nitrate (NO_3^-).

The results of analysis should show that the sum of cations (meq/l) in the analysed water sample is appropriately equal to the sum of anions (meq/l). Some laboratories report the values of SO_4^{2-} to be equal to the difference between the sums of the cations (Na^+, K^+, Ca^{2+} and Mg^{2+} in meq/l) and the sum of the anions (CO_3^{2-}, HCO_3^{1-}, Cl^-, and NO_3^- in meq/l). This is usually done to save time and because SO_4^{2-} values are not needed to calculate the sodium adsorption ratio (SAR) or the residual sodium carbonate (RSC) values in water.

3.2.1 Measurement of water reaction

Water reaction (pH) is a numerical measure of the acidity or basicity of water. The pH is defined as the negative logarithm of the hydrogen ion activity in water. The pH of most water samples ranges between 6 and 8.

Protocol 1. Water reaction measurement	
Apparatus	• pH metre • glass beakers - 25 ml
Reagents	• Standard pH buffer solutions, • Standard pH 7 buffer solution (to calibrate the pH metre)

continues ➡

Water reaction measurement (*continued*)	
Procedure	The pH metre is standardized using the standard pH buffers, with ample rinsing of the electrode with deionized water each time it is dipped into a buffer solution An adjustment for temperature correction is to be made according to the instructions usually provided with the buffer: 1. Transfer about 20 ml of the water sample into a 25 ml tall beaker. 2. Carefully rinse the electrode with deionized water and inmerse it into the water sample. 3. Raise and lower the beaker repeteadly to have better contact between the electrode and the water sample. Record the pH reading.

3.2.2 Measurement of water salinity

The most important water quality parameter from standpoint of salinity is the total concentration of dissolved salts, measured as electrical conductivity (EC). From the EC values, the total salt concentration in the water can be calculated.

The EC values are measured in Siemens per metre (S/m). Many laboratories measure EC in microSiemens (µS) per cm or milliSiemens (mS) per cm, according to the salinity level. Some appropriate conversions from EC to other relationships are:

- dS/m = mS/cm = 1 000 µS/cm;
- mS/cm X 640 = mg/l of total dissolved solids (TDS) in water; and
- mS/cm X 10 = mmoles of charge per litre of either cations or anions.

Protocol 2. Water salinity measurement	
Apparatus	Electrical conductivity metre
Reagents	Analysis with potassium chloride (KCl) solutions: • **Solution A, 0.1 M:** dissolve 7.456 g of oven dried KCl in deionized water. Fill the 1 litre volumetric flask to the mark. This solution has a conductivity of 12.9 mS/cm at 25 °C. • **Solution B, 0.01 M:** transfer 100 ml of Solution A into a 1 litre volumetric flask and fill to the mark. Alternatively, dissolve 0.7456 g of oven dried KCl in deionized water and fill the 1 litre volumetric flask to the mark. This solution has a conductivity of 1.412 mS/cm at 25 °C.
Procedure	1. The electrode is washed with deionized water and rinsed with solution B. 2. Pour some solution B into a 25 ml beaker and dip the electrode. The conductivity metre is adjusted to read 1.412 mS/cm, corrected to 25 °C. 3. The electrode is washed and dipped in the water sample. 4. The digital display is recorded, corrected to 25 °C. The reading in mS/cm of electrical conductivity is a measure of the soluble salts content in the water, and an indication of its salinity status.

3.2.3 Measurement of sodium and potassium

Protocol 3. Sodium (Na^+) and potassium (K^+) ion measurement	
Apparatus	Flame photometer
Reagents	Standard Na and K solutions, prepared in a range of: • Sodium solutions: 0-50 mg/l • Potassium solutions: 0-25 mg/l
Procedure	1. Switch on the flame photometer and let it warm-up for 15-30 minutes. 2. Calibrate the instrument with a blank (deionized water) sample and the standard solutions. 3. Fill the capsules with the sample water. 4. Insert the suction tubing in the capsules and record the reading. 5. Dip the tubin in deionized water to wash the system and read the water sample. 6. Sample readings return sodium or potassium concentration in mg/l (ppm).

3.2.4 Measurement of calcium and magnesium

Protocol 4. Calcium (Ca^{2+}) and potassium (Mg^{2+}) ion measurement	
Apparatus	• Burette - 50 ml • 100-150 ml Erlenmeyer flask
Reagents	• **Ammonium chloride (NH_4Cl) & ammonium hydroxide (NH_4OH) buffer solution:** dissolve 67.5g of NH_4Cl in 570 ml of concentrated NH_4OH. Dilute with deionized water to 1 litre. • **Sodium hydroxide (NaOH) ≈4 N:** dissolve 160 g of NaOH in 1 litre of deionized water. • **Calcium chloride ($CaCl_2$) standard 0.01 N:** dissolve 0.5 g of $CaCl_2$ in 10 ml of HCl 3 M and dilute to 1 litre with deionized water. • **Eriochrome black T indicator:** dissolve 0.5 g of Eriochrome black T and 4.5 g of hydroxylamine hydrochloride in 100 ml of 95% ethanol. • **Calred indicator:** 2-Hydroxy-1-(2-Hydroxy-4 Sulfo-1-Naphthyle 20)-3-Naphtholic acid-original salt. • **Ethylenediaminetetraacetate (EDTA) ≈ 0.01 N:** dissolve 2.0 g of EDTA in 1 litre of deionized water. The solution is standardized against 0.01 N standard $CaCl_2$ solution.

continues ➡

Calcium (Ca^{2+}) and potassium (Mg^{2+}) ion measurement protocol *(continued)*	
Procedure	To measure Ca^{2+}: 1. Pipette an aliquot of water sample (20-25 ml) into a 100-150 ml Erlenmeyer flask. 2. Add 2 ml of 4M NaOH and 2-3 mg of calred indicator. 3. Slowly tritrate with 0.01 N EDTA until obtaining a sky-blue endpoint solution. If the sample is over titrated with EDTA, it can be back titrated with the standard 0.01 N Ca_2Cl. 4. Repeat steps 2 to 3 with a 20-25 ml deionized water blank.
Calculation*	Ca^{2+} (*meq/l*) = EDTA (*ml*) x N EDTA x 10^3 / aliquot (*ml*)
Procedure	To measure Ca^{2+} and Mg^{2+}: 1. Pipette an aliquot of water sample (20-25 ml) into a 100-150 ml Erlenmeyer flask. 2. Add 5 ml of NH_3Cl-NH_4OH buffer solution and 3 to 4 drops of Eriochrome black T indicator. 3. Slowly tritrate with 0.01 N EDTA until obtaining a sky-blue endpoint solution. 4. Repeat steps 2 to 3 with a 20-25 ml deionized water blank.
Calculation*	Ca^{2+} + Mg^{2+} (*meq/l*) = EDTA (*ml*) x N EDTA x 10^3 / aliquot (*ml*) Mg^{2+} (*meq/l*) = (Ca^{2+} (*meq/l*) + Mg^{2+} (*meq/l*)) - Ca^{2+} (*meq/l*)

* Units are indicated in italics.

3.2.5 Measurement of carbonate and bicarbonate

Protocol 5. Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) measurement	
Apparatus	• Burette - 50 ml • 100-150 ml Erlenmeyer flask
Reagents	• **Sulphuric acid (H_2SO_4) ≈0.01 N standard solution.** • **Phenolphthalein indicator solution:** dissolve 0.25 g of phenolphthaleine in 100 ml of 60% alcohol. • **Methyl orange indicator solution:** dissolve 0.1 g of methyl orange in 100 ml of deionized water (0.01%).
Procedure	1. Pipette an aliquot of water sample (20-25 ml) into a 100-150 ml Erlenmeyer flask. 2. Add 4 or 5 drops of phenolphthalein indicator solution. The appearance of a pink colour indicates the presence of carbonates in the sample. 3. Place the flask on the magnetic stirrer. 4. Slowly tritrate with the H_2SO_4 solution (0.01 M), adding a drop every 2-3 seconds until the pink colour disappears. 5. Record the volume of H_2SO_4 used (V_1). 6. Add 4 or 5 drops of methyl orange solution to the colourless solution.

continues ➡

Carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) measurement protocol *(continued)*	
Procedure	7. Without refilling the burette, continue the tritration until obtaining a pink endpoint solution. 8. Record the total volume of H_2SO_4 used (V_2). 9. A blank correction is made for the methyl orange titration.
Calculation*	CO_3^{2-} (*meq/l*) = 1 000 / aliquot (*ml*) x $2V_1$ x N H_2SO_4 HCO_3^- (*meq/l*) = 1 000 / aliquot (*ml*) x N H_2SO_4 x (V_2 - $2V_1$)

* Units are indicated in italics.

3.2.6 Measurement of chloride

Protocol 6. Chloride (Cl^-) measurement	
Apparatus	• Burette - 50 ml • 100-150 ml Erlenmeyer flask
Reagents	• **Potassium chromate (K_2CrO_4) indicator 5%:** dissolve 5 g of K_2CrO_4 in 90 ml of deionized water. Add 1 N of silver nitrate ($AgNO_3$) solution drop by drop until some brownish-red, silver chromate ($AgCrO_4$) precipitates. Store the solution in the dark for 24 hours. If a precipitate forms, filter the solution and top to 100 ml. • **Silver nitrate ($AgNO_3$) standard, 0.005 N:** dissolve 0.8495 g of $AgNO_3$ in deionized water and dilute to 1 litre (keep in brown bottle away from light).

continues ➡

Chloride (Cl^-) measurement protocol *(continued)*	
Procedure	1. Pipette an aliquot of water sample (20-25 ml) into a 100-150 ml Erlenmeyer flask. 2. Add 4 or 5 drops of K_2CrO_4 indicator. 3. Slowly tritrate with the $AgNO_3$ standard under bright light until the first permanent brownish-reddish endpoint solution. 4. Prepare a blank to: a) correct for the amount of Ag^{2+} used to form the Ag_2CrO_4 precipitate; and b) use as a reference for the end point.
Calculation*	Cl^- (*meq/l*) = 1 000 / aliquot (*ml*) x $AgNO_3$ (*ml*) - $AgNO_3$ blank (*ml*) x N $AgNO_3$

* Units are indicated in italics.

3.2.7 Measurement of nitrate by the specific ion electrode

The concentration of nitrate-nitrogen (NO_3-N) is estimated by comparison of the electromotive force (emf in millivolts) in the unknown with that in the NO_3-N standards prepared by the same method.

Protocol 7. Nitrate-nitrogen (NO_3-N) measurement	
Apparatus	pH – millivolt metre or specific ion metre, with specific nitrate electrode and reference electrode.

continues ➡

Nitrate-nitrogen (NO_3-N) measurement protocol *(continued)*	
Reagents	• **Standard nitrate-nitrogen (NO_3-N) solutions:** dissolve 7.22 g of dry KNO_3 in 1 l of deionized water to obtain the stock solution of 1 000 mg NO_3-N/l. From it, prepare a series of standards in deionized water ranging from 1 to 50 mg NO_3-N/l. • **Ammonium sulfate ($(NH_4)_2SO_4$) 2 M solution:** dissolve 264 g of reagent grade $(NH_4)_2SO_4$ in 1 l of deionized water. This solution is used for ionic strength adjustment.
Procedure	1. Add a 50-100 ml aliquot of the water sample in a 200 ml beaker. Add 3 ml of $(NH_4)_2SO_4$ solution. 2. Place the beaker on a magnetic stirrer. 3. Insert the electrodes into the solution and start stirring. 4. Record the multi-volt reading (if using a calibration curve). If a specific ion metre is used, directly read the concentration.

3.2.8 Measurement of ammonium by specific ion electrode

The sample and standards are made alkaline by the addition of sodium hydroxide (NaOH), reaching pH of 11-12, as the electrode responds only to ammonia (NH_3) activity. The metre should be calibrated immediately before each series of analysis. Measurements should be made 1-2 minutes after the addition NaOH to ensure no loss of ammonia.

Protocol 8. Ammonium (NH_4^+) measurement	
Apparatus	• Ammonia electrode • pH-millivolt metre with sensitivity of 0.1 millivolts at least
Reagents	• **Sodium hydroxide (NaOH) 0.25 M solution:** dissolve 10 g of NaOH in 800 ml of deionized water and dilute to 1 l. • **Potassium chloride (KCl) 2M solution:** dissolve 150 g of reagent-grade KCl in 1 l of deionized water. • **Standard ammonium (NH^{4+}) solution:** dissolve 0.4717 g of ammonium sulfate $(NH_4)_2SO_4$ in deionized water and dilute to 1 l. If pure, dry $(NH_4)_2SO_4$ is used, the solution contains 100 µg of ammonium nitrogen (NH^{4+}-N) per ml (100 mg/l). The solution is stored in a refrigerator. Immediately before use, dilute 2 ml of the stock solution in 200 ml of deionized water. The resulting working solution contains 1µg of NH^{4+}-N/ml (1 mg/l). A series of standards is prepared in 2 M potassium chloride (KCl) ranging from 0.1 to 10 µg of NH^{4+}-N/ml.

continues ➡

Ammonium (NH_4^+) measurement protocol *(continued)*	
Procedure	1. Add a 50-100 ml aliquot of the water sample in a 200 ml beaker. 2. Add 3 ml of 0.25 M NaOH solution and insert the NH_3 electrode that is connected to a pH-multivolt metre. 3. Stirr the solution for a minute and calculate the NH_4-N value from the calibration curve.

3.2.9 Measurement of sulfate by precipitation as barium sulfate

Protocol 9. Sulfate (SO_4^-) as barium sulfate ($BaSO_4$) measurement	
Apparatus	• Spectrophotometer • Volumetric flask
Reagents	• **Acetic acid (CH_3COOH), 50%:** 50 ml acetic acid is added to 50 ml deionized water. • **Ortho-phosphoric acid (H_3PO_4), concentrated** • **Barium chloride ($BaCl_2$) crystals:** ground the crystals to pass a 0.5 mm sieve and retained on a 0.25 mm sieve. • **Gum acacia solution, 0.25% (w/v) in water.** • **Standard sulfate (SO_4^{2-}) solution:** dissolve 147.9 mg of anhydrous sodium sulfate (Na_2SO_4) in 200 ml of deionized water and dilute to 1 l. This solution contains 100 µg SO_4^{2-}/ml (100 mg SO_4^{2-}/l).

continues ➡

Sulfate (SO_4^-) as barium sulfate ($BaSO_4$) measurement protocol *(continued)*	
Procedure	1. Pipette a 20-30 ml of the water sample into a 50 ml volumetric flask. 2. Add 5 ml of CH_3COOH, 1 ml of H_3PO_4 and 1 g of $BaCl_2$ crystals. The phosphoric acid will decolourise any iron present in solution. Mixing is done gently by inverting the flask several times. 3. Add 2 ml of gum acacia solution. Add deionized water to volume. 4. Mix gently again and at 5 minutes (±30 seconds. 5. Measure $BaSO_4$ turbidity with a spectrophotometer at 420 nm. 6. SO_4^{2-} concentration is estimated in sample by comparing turbidity with a calibration curve prepared by carrying sulfate standards through the entire procedure.

3.2.10 Measurement of sulfate by precipitation as calcium sulfate

The conductivity of the solution changes with the ion electrode concentration and temperature. Table 2 summarizes the conductivity values for different concentrations at 25 °C.

Protocol 10. Sulfate (SO_4^-) as calcium sulfate ($CaSO_4$) measurement	
Apparatus	• Electrical conductivity metre • Centrifuge and 50 ml tubes

continues ➡

Sulfate (SO_4^-) as barium sulfate ($BaSO_4$) measurement protocol *(continued)*	
Reagents	• **Acetone ($(CH_3)_2CO$), analytical grade.**
Procedure	1. Transfer a 30 ml aliquot of the water sample into a 50 ml centrifuge tube. 2. Add 30 ml of $(CH_3)_2CO$, mix and allow to stand for 15 minutes or until the precipitate flocculates. 3. Centrifuge the tube at 2 000 rpm for 3 minutes. Carefully decant the supernatant and invert the tube on a clean filter paper. Let drain for 5 minutes. 4. Add 40 ml of deionized water to the tube, cover it with a stopper and shake it until the precipitate is completely dissolved. 5. Measure the solution's EC and correct the conductivity reading to 25 °C. 6. The SO_4^{2-} concentration in water sample is determined in Table 2.

3.2.11 Measurement of trace elements

Measurement of element concentration using atomic absorption spectroscopy (AAS) has become a common practice in almost all laboratories, especially for the measurement of trace elements concentration in solutions. Each atomic absorption spectrophotometer has its instruction manual that guides the user to the adjustment and operation of the instrument. Nevertheless, it is essential to have a general knowledge of the basic principles of the technology.

Table 2. Electrical conductivity values for different calcium sulfate concentrations in water

$CaSO_4$ concentration (meq/l)	EC at 25 C (mS/cm)
1	0.121
2	0.226
5	0.500
10	0.900
20	1.584
30.5	2.205

Source: Richards, L.A. 1954. Diagnosis and improvement of saline and alkali soils. USDA Agricultural Handbook No. 60. US Department of Agriculture, Washington DC.

AAS uses absorption of light to measure the concentration of analyte atoms in a flame or graphite furnace. The light source is usually a hollow-cathode lamp of the element that is being measured. Lamps convert electrical energy into radiation. Atoms absorb the radiation and make transitions to higher energy levels. Light absorption is proportional to the number of analytes atoms in the path of light. Concentration measurements are determined from a working curve after calibrating the instrument with standards of known concentration.

Figure 18. Atomic absorption spectrometers in the laboratory of Tripoli

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AAS requires that the analytes' atoms be in the gas phase. Ions or atoms in a sample must undergo vaporization or atomization in a high-temperature source such as a flame or graphite furnace. Flame AAS uses a slot type burner to increase the path length, and therefore to increase the total absorbance. Sample solutions are usually aspirated with the gas flow into a nebulizing/mixing chamber to form small droplets before entering the flame.

Furnace AAS is a much more efficient atomizer than the flame and can directly accept very small quantities of sample. The furnace is electrically heated in several steps to dry the sample, ash organic matter, and vaporize the analytes' atoms. While flame AAS measures concentration of analyte in µg/ml (ppm, parts per million, 10^{-6}), furnace AAS detects concentrations in µg/l (ppb, parts per billion, 10^{-9}).

A calibration curve is a plot of the analytical signal (the instrument or detector response) as a function of analytes concentration. These calibration curves are obtained by measuring the signal from a series of standards of known concentration. The calibration curves are then used to determine the concentration of an unknown sample.

To measure the trace elements, the following procedures should be followed:

- An intermediate standard stock solution is prepared by pipetting 10 ml from the 1 000 µg/ml stock solution of the analyte into a 200 ml volumetric flask and diluted to the volume.
- Standard solutions are prepared in the working range such as 0, 1, 2, 5 or 10 µg/ml of the trace metal.
- The instruction manual is follwed to optimize the working condition of the instrument.
- The signals from the series of working standards of known concentration are measured and the analytical signals (the instrument or detector response) are plotted as a function of analyte concentration.
- In modern instruments, the signals and elemental concentration are directly shown on a screen.

3.2.12 Measurement of boron by colour development

Protocol 11. Boron (B) by colour development	
Apparatus	• Analytical balance • Flask or beaker • Volumetric flask • Funnels • Whatman No.42 filter paper or equivalent • Spectrophotometer
Reagents	• **Azomethine-H:** dissolve 0.45 g of azomethine-H and 1.0 g of L-ascorbic acid in 100 ml deionized water. If solution is not clear, gently heat it in a water bath or under a hot water tap at about 300 °C until it dissolves. A fresh solution should be prepared weekly and kept in a refrigerator. • **Buffer solution:** dissolve 250 g of ammonium acetate ($NH_4CH_3CO_2$) in 500 ml deionized water. Adjust the pH to about 5.5 by slowly adding approximately 100 ml of glacial acetic acid (CH_3COOH), with constant stirring. • **EDTA solution (0.025 M):** dissolve 9.3 g of EDTA in deionized water. Make the volume up to 1 l.

continues ➡

Boron (B) by colour development protocol (*continued*)	
Reagents	• **Standard stock solution:** dissolve 0.8819 g of AR-grade borax ($Na_2B_4O_7 \cdot 10H_2O$) in a small volume of deionized water. Make the volume up to 1 l. This solution has a boron concentration of 100 µg B/ml. • **Working standard solution:** 5 ml of stock solution is taken in a 100 ml volumetric flask and diluted it to the mark. This solution contains 5 µg B/ml (5mg B/l).
Procedure	Azomethine-H colour solution procedure: 1. Transfer a 10-30 ml aliquot into a 50 ml volumetric flask. Add 2 ml of buffer solution, 4 ml of EDTA solution and 4 ml of azomethine-H solution. Mix thoroughly after the addition of each reagent. 2. Let the solution stand for 1 hour to allow colour development and make the volume to the mark. The colour of the solution developed as described is stable for 3 to 4 hours.

continues ➡

Boron (B) by colour development protocol (*continued*)	
Procedure	Standard curve preparation: 1. Add 0, 0.5, 1.0, 2.0, 4.0 and 8.0 ml of the working standard solution to a series of 50 ml volumetric flasks. 2. Add 4 ml each of buffer reagent, EDTA solution and azomethine-H solution. Mix the contents after each addition and allow the flasks to stand at room temperature for 30 minutes 3. Make the volume to 50 ml with deionized water. 4. Measure absorbance at 420 nm. This reading provides the references for the standard solution at 0, 0.05, 0.10, 0.20, 0.40 and 0.80 µg B/ml.
Calculation*	B (*mg/l*) = 1 000 / aliquot (*ml*) x reading from standard solution (*mg B/l*)

* Units are indicated in italics.

3.2.13 Measurement of phosphorous

Protocol 12. Phosphorous (P) by Olsen's method	
Apparatus	• Spectrophotometer • Funnels and filter papers
Reagents	**Preparation of the ammonium molybdate ($(NH_4)_6Mo_7O_{24} \cdot 4H_2O$) solution:** • Dissolve 12 g of ($(NH_4)_6Mo_7O_{24} \cdot 4H_2O$) in 250 ml of deionized water.

continues ➡

Phosphorous (P) by Olsen's method (*continued*)

Reagents

- Add 0.291 g of antimony potassium tartrate ($K_2Sb_2(C_4H_2O_6)_2$) in 100 ml of ionized water.
- Add both solutions to 1 l of H_2SO_4 2 M and make the volume to 2 000 ml with deionized water. Store in the refrigerator.
- **Ammonium molybdate – ascorbic acid solution:** Dissolve 1.056 g of ascorbic acid ($C_6H_8O_6$) in 200 ml of ammonium molybdate solution and mix. Prepare only the amount anticipated, as this solution is not stable for more than 24 hours.
- **Standard phosphate (PO_4^{3-}) solution:** dissolve 0.4393 g of previously dried at 40 °C monopotassium phosphate (KH_2PO_4) in deionized water and make the volume to 1 l. This solution contains 100 µg of P/ml (100 mg P/l).
- **Working standard (dilute) phosphate solution:** dilute 50 ml of the standard phosphate solution into 950 ml of deionized water This solution contains 5 µg of P/ml (5 mg P/l).
- **Sulfuric acid (H_2SO_4), 2.5 M:** add 140 ml of concentrated H_2SO_4 (18 M) to 800 ml of deionized water. Make the volume to 1 l with deionized water.

continues ➡

Phosphorous (P) by Olsen's method (*continued*)

Procedure

1. Filter a water sample through a Whatman No. 40 filter paper into a clean and dry 125 ml Erlenmeyer flask.
2. Transfer a 10-25 ml of filtrate to a 100-150 ml volumetric flask.
3. Add 8 ml of the ammonium molybdate – ascorbic acid solution and make the volume to 50 ml. Mix well and let stand for 10 minutes.
4. Read the absorbance is read at 882 nm on the spectrophotometer. The colour is stable for 12 hours and maximum intensity is obtained after 10 minutes.
5. Determine the P concentration using the calibration curve that translates absorption units into P concentration in µg P/ml.
6. Standard curve preparation: prepare a series of 0, 2, 5, 10, 15 and 20 ml of 5 µg P/ml from the standard stock solution in 50 ml volumetric flasks. Develop the colour as described above.

3.2.14 Evaluation of water salinity

The concentration and composition of soluble salts in water determine its quality for various purposes (drinking, irrigation, industry, etc.).

There are 4 criteria for evaluating water quality to irrigation purposes.

1. Total content of soluble salts (salinity).
2. Ratio of Na^+ to Ca^{2+} and Mg^{2+} ions (SAR).
3. Residual sodium carbonate (RSC) HCO_3^- + CO_3^{2-} in relation to Ca^{2+} + Mg^{2+}.
4. Excessive concentrations of elements that may cause plant toxicity (ionic imbalance in plant tissue).

Water salinity

Most soluble salts in water are composed of the cations Na^+, Ca^{2+} and Mg^{2+} and anions Cl^-, HCO_3^- and SO_4^{2-}. Relatively smaller quantities of K^+, NH^{4+}, NO_3^- and CO_3^{2-} also occur, so do many other ions.

Rainwater contains negligible amounts of salt in many locations, but rain in coastal areas often contains 30 mg or more salt per litre due to interaction of sea salt and rain in a windy weather. Generally, rain is not considered a source of soil salt and it is the primary means of salt removal from the soil.

Excess salts concentration in irrigation water increases the osmotic pressure of the soil solution that can result in physiological drought conditions. This occurs because the plant roots are unable to take up soils water due to its high osmotic potential. The following conversions are important to understand before salinity is interpreted:

- 1dS/m = 1mS/cm = 1 000 µS/cm
- mS/cm X 640 = mg/l of total dissolved solids (TDS) in water
- mS/cm X 10 = mmoles of charge/l of either cations or anions

The salinity of irrigation water is classified, and the level of severity interpreted as per the salinity classes. Table 3 shows the corresponding severity level.

Table 3. Salinity of irrigation water and its salt contents

Salinity of irrigation water (µS/cm)	Salinity class	Salinity level
100-250	C1	Low
250-750	C2	Medium
750–2 250	C3	High
>2 250	C4	Very high

Sources: 1) Zaman, M., Shahid, S.A. & Heng, L. 2018. Irrigation water quality. In: *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques.* Springer, Cham. 2) Bauder, T.A., Waksom, R.M., Sutherland, P.L & Davis, J.G. 2011. *Irrigation water quality criteria.* Colorado State University Extension Publication. Fact sheet No. 0.506 3) Follet, R.H. & Soltanpour, P.N. 2002. *Irrigation water quality criteria.* Colorado State University. Fact sheet No. 0.506

Salinity levels determine whether the water can be used for irrigation, as shown in Table 4 (Zaman, 2018; Bauder *et al.*2011; Follett and Soltanpour 2002):

- Class C1 – low salinity water: it can be used for irrigation of crops on all soils. Leaching of salts usually occur normally, except for soils with extremely low permeability.
- Class C2 – medium salinity water: it can be used if a moderate amount of leaching can occur. Plants with moderate salt tolerance can be grown without special practices for salinity control.
- Class C3 – high salinity water: it cannot be used in soils with restricted drainage. Plants with salt tolerance should always be selected.
- Class C4 – very high salinity water: it is not suitable for irrigation water under ordinary conditions. It may be used occasionally under very special circumstances. Very permeable soil, adequate drainage, excess irrigation water to be applied and only very salt tolerant crops should be selected.

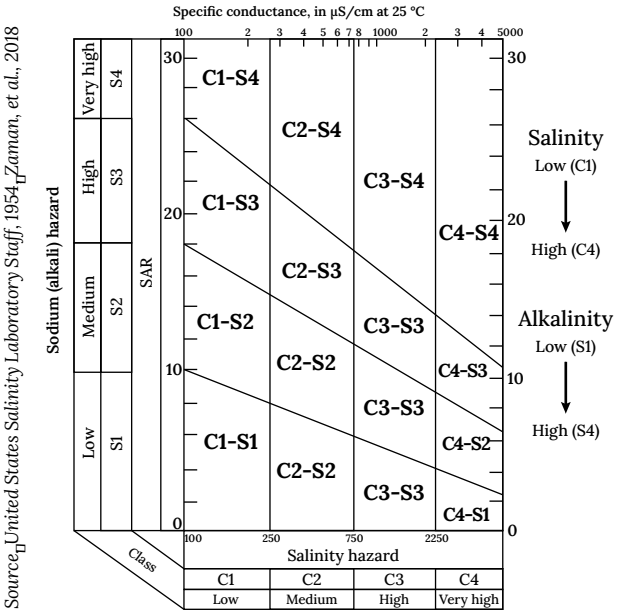
Table 4. Salinity of irrigation water and its salt contents

Hazard	Dissolved salt content	
	ppm (mg/l)	EC (µS/cm)
None: no detrimental effects will usually be noticed.	up to 500	up to 750
Some: may have detrimental effects on sensitive crops	500 to 1 000	750 to 1 500
Moderate: may have adverse effects on many crops, thus requiring careful management practices	1 000 to 2 000	1 500 to 3 000
Severe: can be used for salt tolerant plants on permeable soils with careful management practices	2 000 to 5 000	3 000 to 7 500

Sources: 1) Zaman, M., Shahid, S.A. & Heng, L. 2018. Irrigation water quality. In: *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques.* Springer, Cham. 2) Bauder, T.A., Waksom, R.M., Sutherland, P.L & Davis, J.G. 2011. *Irrigation water quality criteria.* Colorado State University Extension Publication. Fact sheet No. 0.506 3) Follet, R.H. & Soltanpour, P.N. 2002. *Irrigation water quality criteria.* Colorado State University. Fact sheet No. 0.506

The United States Salinity Laboratory classified irrigation water according to its content in soluble salts and sodium as shown in Figure 19.

Figure 19. United States Salinity Laboratory diagram for classification of irrigation water



Source: United States Salinity Laboratory Staff, 1954; Zaman, et al., 2018

Sodium hazard

Sodium hazard of irrigation water is expressed as sodium adsorption ratio (SAR). Sodium may be toxic to sensitive crops such as fruits trees. Another problem with sodium concentration is its bad effect on the physical properties of soils. Continued use of water with high SAR leads to the breakdown of soil structure.

Sodium adsorption rate (SAR) can be calculated as follows:

- $SAR\ (meq/l) = Na^{+} / \sqrt{(1/2\ (Ca + Mg)\ )}$
- $SAR = Na / \sqrt{((Ca + Mg)\ )}$

Concentrations of Na^{+}, Ca^{2+} and Mg^{2+} are expressed in milliequivalent per litre (meq/l)
Concentrations of Na^{+}, Ca^{2+} and Mg^{2+} are expressed in millimole per litre (mmole/l)

The classification of sodium adsorption ratio defines the suitability of the irrigation water. The ranges of SAR values are summarized in Table 5.

Table 5. SAR classes of irrigation water

SAR of irrigation water	Sodicity class	Level
<10	S1	Low
10-18	S2	Medium
18-26	S3	High
>26	S4	Very high

Source: Richards, L.A. 1954. *Diagnosis and improvement of saline and alkali soils.* USDA Agriculture Handbook. US Department of Agriculture, Washington DC, USA.

The salinity level determines whether the water can be used for irrigation:

- Class S1 – low sodium water: it can be used on almost all soils with little or no danger without the soil developing harmful levels of exchangeable Na.
- Class S2 – medium sodium water: it will present an appreciable Na hazard in fine textured soils with high cation exchange capacity (CEC). It may be used in coarse textured or organic soils with good permeability.
- Class S3 – high sodium water: it may produce harmful levels of exchangeable Na in most soils. Its use will require special soil management methods and use of chemicals, which encourage the replacement of exchangeable Na. Gypsiferous soils often will not develop high levels of exchangeable Na.
- Class S4 – very high sodium water: it is generally unsatisfactory for irrigation except at low salinity levels. The use of gypsum or other chemicals makes its use more feasible.

Adjusted Sodium Adsorption Ratio

Under field conditions, the exchangeable sodium percentage (ESP) value in topsoil is very close to the value of the adjusted SAR, where corrected pH value (pH e) is calculated as the pH used in the Langelier Index of the irrigation water. Ayers and Westcot (1985) presented the term adjusted SAR (SAR adj) as:

- $SARadj = SARiw [1 + (8.4 - pHe)]$

The Langelier index is based on calculations of the pH which a given water would achieve when in equilibrium with solid phase of calcium carbonate ($CaCO_3$) at average carbon dioxide (CO_2) values. This pH, when compared to the initial pH of the water, can be used to predict whether $CaCO_3$ should precipitate from or be dissolved by the water as it passes through calcareous soils (Balba, 1995). The pHe is the theoretical pH that water could have in equilibrium with $CaCO_3$

3.2.15 Residual sodium carbonate

The residual sodium carbonate (RSC) approach has been widely used to predict the additional sodium hazard, which is associated with $CaCO_3$ and magnesium carbonate ($MgCO_3$) precipitation. RSC can be calculated as the following:

- $RSC = (CO_3 + HCO_3) - (Ca + Mg)$,

The approach of SAR is more commonly used but knowing both values of SAR + RSC will give a clearer idea about the sodium hazard and possibility of $CaCO_3$ and $MgCO_3$ precipitation in the soil solution after irrigation or even in the canals or water pipes. The RSC ranges define the suitability for irrigation, as shown in Table 6.

Table 6. RSC and suitability of water for irrigation

SAR of irrigation water	Sodicity class
<1.25	Safe
1.25-2.5	Marginal
>2.5	Unsuitable

Sources: 1) Eton, F.M. 1950. Significance of carbonates in irrigation waters. *Soil Sci* 69:123-133 2) Wilcox, L.V., Blair, G.Y. & Bower, C.A. 1954. Effect of bicarbonate on suitability of water for irrigation. *Soil Sci* 77:259–266

3.2.16 Toxicity of elements

In addition to salinity and sodium hazard, some crops may be sensitive to the presence of high concentration of specific ions in irrigation water. Toxicity to crops may result from chlorides, boron, sodium and many trace elements.

Sodium (Na)

Sodium toxicity may cause leaf burn, leaf scorch and dead tissue starting from the outside edges of the leaves. However, toxicity usually starts at the leaf tip. Correct diagnosis can be made from plant tissue analysis. In tree crops, Na concentration higher than 0.25-0.50 percent in the leaf tissue is considered a toxic level.

Chloride (Cl)

In irrigation water, the most common crop toxicity is caused by chlorides (Cl^-). Water must be analysed for Cl^- concentration when assessing its quality.

In sensitive crops (blackberry, grapefruit, orange, peach, walnut, onion, etc.), symptoms occur when chloride levels accumulate in the leaves (0.3-1.0 percent). The toxicity of Cl appears first at the leaf tips and progress back along the edges, as severity of the toxicity increases. Excessive necrosis is often accomplished by early leaf drop or even almost total plant defoliation.

Table 7. Chlorides levels in irrigation water and their effects on crops

Cl^- concentration (mg/l) (ppm)	Effect on crops
<70	Safe for all crops
70-140	Moderate injury for sensitive crops
141-350	Moderately tolerant plants usually show some injury
>350	Can cause severe problems

Sources: 1) Eton, F.M. 1950. Significance of carbonates in irrigation waters. *Soil Sci* 69:123-133 2) Wilcox, L.V., Blair, G.Y. & Bower, C.A. 1954 Effect of bicarbonate on suitability of water for irrigation. *Soil Sci* 77:259-276

Boron (B)

Plants require low amounts of boron (B) and if it exceeds a certain level, depending on the crop tolerance, it may cause injury. The difference between deficiency and toxicity of boron for many crops is narrow.

A concentration of 0.03 mg/l of boron in water is sufficient. However, to avoid toxicity, boron concentrations in water should be lower than 0.3 mg/l. Boron toxicity is not a problem for most plants grown in soils with high free $CaCO_3$ (lime); usually they tolerate higher levels of boron than those grown in non-calcareous soils. The range of boron concentration defines the suitability of water for irrigation, as shown in Table 8.

Table 8. Boron concentration in irrigation water

Boron concentration (mg/l) (ppm)	Class
<0.5	Satisfactory for all crops
0.5 - 1.0	Moderate
1.0 - 2.0	Slightly high
2.0 - 5.0	High
>5.0	Very high

Sources: 1) Zaman, M., Shahid, S.A. & Heng, L. 2018. Irrigation water quality. In: *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques.* Springer, Cham. 2) Bauder, T.A., Waksom, R.M., Sutherland, P.L & Davis, J.G. 2011. *Irrigation water quality criteria.* Colorado State University Extension Publication. Fact sheet No. 0.506 3) Follet, R.H. & Soltanpour, P.N. 2002. *Irrigation water quality criteria.* Colorado State University. Fact sheet No. 0.506

3.2.17 Trace elements

The concentration of trace elements in irrigation water affects the quality of water and its suitability for irrigation, drinking or industry. Some of these elements are needed for plant growth and are absorbed by plants in small quantities such as iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), molybdenum (Mo) and nickel (Ni).

Other trace elements that may be present in the water may be harmful if present in high concentrations like arsenic (As), lead (Pb), cadmium

(Cd), cobalt (Co), chromium (Cr), mercury (Hg) etc. All these minerals can be measured by the atomic absorption spectrophotometry "flameless mode" or other instruments.

Very often, the presence of concentrations higher than the accepted limits indicate industrial contamination source that should be detected and stopped.

3.2.18 Interpretation of results of chemical analysis and the limits

Considering the annual irrigation rate of 10 000 m^3/ha, the protocol recommends the following threshold as acceptable values. The threshold values are consistent with the National Water Quality Management Strategy (ANZECC and ARMCANZ, 2000) and WHO guidelines bulletins (Ayers and Westcott, 1985; Morris and Devitt, 1991; Blumenthal *et al.*, 2000).

Table 9. Threshold values of chemical analysis

Test	Acceptable values	Comments
Turbidity	35 NTU	>70 NTU (causes drip irrigation blockage)
Electrical conductivity (EC)	2.0 dS/m	> 4 dS/m (toxic)
Total dissolved solids (TDS)	700 mg/l	2 000 mg/l (toxic)
Sodium adsorption ratio (SAR)	<10	>15 (toxic)
pH	6.5-8.4	Normal range
Bicarbonate (HCO_3^-)	300 mg/l	>500 mg/l (check RSC)
Chloride (Cl^-)	200 mg/l	>300 mg/l
Residual chlorine	--	>0.05 mg/l (damage some crops)
Sulfate (SO_4^{2-})	400 mg/l	Normal
Nitrate-nitrogen (NO_3-N)	5-30 mg/l	Contributes to algal growth and eutrophication
Phosphorus (P)	<2 mg/l	Contributes to algal growth and eutrophication
Iron (Fe)	0.1 mg/l	>0.1 mg/l (very high)
	1.5 mg/l (calcareous soils)	>3 mg/l (very high)
Zinc (Zn)	0.1 mg/l	>0.2 mg/l (very high)
	2.0 mg/l (calcareous soils)	>4 mg/l (very high)
Copper (Cu)	0.03 mg/l	>0.06 mg/l (very high)
	0.20 mg/l (calcareous soils)	>0.4 mg/l (toxic)

continues ➡

Table 9. Threshold values of chemical analysis *(continued)*

Test	Acceptable values	Comments
Manganese (Mn)	0.05 mg/l	>0.1 mg/l (very high)
	0.2 mg/l (calcareous soils)	>0.4 mg/l (very high)
Molybdenum (Mo)	0.01 mg/l	>0.02 mg/l (very high)
Selenium (Se)	0.02 mg/l	0.04 mg/l (toxic)
Boron (B)	<2mg/l	>4 mg/l (toxic)
Cadmium (Cd)	0.02 mg/l	>0.04 mg/l (reduces crop quality)
Nickel (Ni)	0.02 mg/l	>0.04 mg/l (reduces crop quality)
Mercury (Hg)	0.01 mg/l	>0.04 mg/l (reduces crop quality)
Lead (Pb)	0.02 mg/l	>0.04 mg/l (reduces crop quality)
Arsenic (As)	0.1 mg/l	>0.2 mg/l (toxic)
Cobalt (Co)	0.05 mg/l	>0.1 mg/l (toxic)
Chromium (Cr)	0.10 mg/l	>0.2 mg/l (toxic)

Sources: 1) ANZECC & ARMCANZ. 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. In: *National Water Quality Management Strategy.* 2) Ayers, R.S. & Wescott, D.W. 1985. *Water quality for agriculture.* FAO irrigation and drainage paper No. 29, rev 1. Rome, FAO. 3) Morris, R. & Devitt, D. 1991. *Sampling and interpretation of landscape irrigation water.* Fact sheet 01-91. University of Nevada, Reno, USA.

3.3 Biological analysis

The biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are important parameters that indicate contamination of water with organic waste.

The BOD is the amount of oxygen required by bacteria to stabilize decomposable organic matter under aerobic conditions.

The COD determines the oxygen required for chemical oxidation of organic matter and oxidizable inorganic substances with the help of a strong chemical oxidant, therefore, COD ≥ BOD.

3.3.1 Biological oxygen demand by respirometry system

Industrial samples often contain toxic substances and require special considerations when running a BOD test.

Protocol 13. Biological oxygen demand (BOD)	
Apparatus	• Brown bottles with sensors. Every bottle has a LED lightening system that shows the drop in pressure developing inside the bottle.

continues ➡

Biological oxygen demand (BOD) protocol *(continued)*	
Apparatus	• Incubator with special amber/brown bottles with inductive stirring units, adapter plug, and seal cap (gasket). Modern equipment is fitted with an individual monitoring and programming system that displays pressure drop (BOD levels) on a special screen outside the incubator.
Reagents	• **Potassium hydroxide (KOH) 12 N** • **Nitrification inhibitor**
Procedure	• Carefully fill the bottles with sample water. Prevent the formation of air bubbles and keep an ample amount of air left above the sample. • Add the sample to the BOD bottle after checking its pH is between 6 and 8 and after removing chlorine. Adjust pH if necessary and add the nitrification inhibitor to the sample. • Place the seal cup on the neck of each bottle. Add lithium hydroxide (LiOH) or potassium hydroxide (KOH) to each seal cup to absorb CO_2 formed inside the bottle. • Add a stirring bar to each bottle and firmly tighten the pressure cap sensor in each bottle. • Place the bottles in the incubator at 20 °C. Program the instrument for each bottle selecting the proper ranges. • Start the test, which usually lasts 5 days. The results of each bottle can be read at any time on the bottles or screen.

The presence of toxic substances in the sample will cause decreased BOD values. The effect of these substances can be eliminated by diluting the sample. Chlorine should be removed by adding sodium thiosulfate ($Na_2S_2O_3$). The BOD concentration informs on the safety of water and the water can be considered polluted from 8-20 mg/l.

Table 10. BOD levels in river water

BOD (mg/l)	Level
< 1	Clean
1-2	Acceptable
2-8	Moderately polluted
8-20	Polluted
>20	Heavily polluted
>200	Untreated sewage

Source: Elaborated by the America University of Beirut from international standard.

3.3.2 Analysis of chemical oxygen demand

The chemical oxygen demand (COD) test measures the oxygen equivalent of the amount of organic matter oxidizable by potassium dichromate in a 50 percent sulfuric acid solution.

The COD test uses a strong chemical oxidant (potassium dichromate), acid (sulfuric acid) and heat to oxidize organic carbon to carbon dioxide and water. The COD measures the amount of dichromate (oxidant) consumed in the breakdown of organic matter. Specifically:

- More oxidant consumed: high levels of organics.
- Less oxidant consumed: low levels of organics.

There are two methods to measure the COD, titrimetric and colourimetric.

3.3.3 Titrimetric determination of chemical oxygen demand

The ferrous (Fe^{2+}) in the FAS is reduced to ferric (Fe^{3+}). The organic compounds in the water are oxidized to CO_2 and their electrons pass to the dichromate, which is reduced from hexavalent chromium (Cr^{6+}) to chromium (III) oxide (Cr^{3+}).

Protocol 14. Chemical oxygen demand (COD) protocol, titrimetric determination

Apparatus	• Erlenmeyer flasks, 500 ml • Reflux system • Magnetic stirrer • Burettes, 10 ml • Thermometer, 200 °C
Reagents	• **Potassium dichromate ($K_2Cr_2O_7$) solution 1 N:** dissolve 49.04 g of $K_2Cr_2O_7$ in water and dilute to 1 litre. • **Concentrated sulfuric acid (H_2SO_4), containing silver sulfate (Ag_2SO_4):** dissolve 25 g of Ag_2SO_4 in 1 litre of 96 %, reagent grade H_2SO_4. • **Ferroin indicator (o-phenanthroline ferrous sulfate) 0.025 M:** dissolve 14.85 g of o-phenanthroline monohydrate and 6.95 g ferrous sulfate in water and dilute to 1 litre. • **Ferrous ammonium sulfate ($(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O$) (FAS, Mohr's salt) 0.5 M:** dissolve 196 g of FAS in water. Add 15 ml of concentrated sulfuric acid and let it cool to room temperature. Dilute to 1 litre. This solution is standardized against 10 ml of $K_2Cr_2O_7$ as indicated below.

continues ➡

Chemical oxygen demand (COD) protocol, titrimetric determination *(continued)*

Procedure	• Add 200 ml of water in a 500 ml wide mouth Erlenmeyer flask. • Add 10 ml of $K_2Cr_2O_7$ 1 N and 20 ml of concentrated H_2SO_4 and reflux at 150°C for two hours. • Place the flask is placed on a heatproof mat and allow it to slowly cool down to room temperature. • Add 4 to 5 drops of Ferroin indicator. Tritrate with 0.5 N FAS until colour changes from yellow to red. • Standardize the reagents using a blank determination in the same manner. • Repeat the analysis with a smaller amount of water (or larger volume of dichromate) if more than 80% of the dichromate solution is reduced.

After all the organic compounds are oxidized, some dichromate is remained. This amount is measured by titration with FAM. The Fe^{2+} in FAM donates electron to the remaining dichromate and oxidized to Fe^{3+}. When the dichromate has all been reduced, the Ferroin indicator detects the presence of the Fe^{2+} ions and changes colour from yellow to red.

3.3.4 Colourimetric determination of chemical oxygen demand

The sample is digested for 2 hours at 150 °C using the COD tubes. Oxidizable organic compounds react reducing the dichromate ion from Cr^{6+} to Cr^{3+} (green colour).

Protocol 15. Chemical oxygen demand (COD) protocol, colourimetric determination	
Apparatus	• Spectrophotometer • COD vials
Reagents	• **Potassium dichromate ($K_2Cr_2O_7$) solution 1 N:** dissolve 49.04 g of $K_2Cr_2O_7$ in water and dilute to 1 litre.
Procedure	High range or low range COD vials are used according to the expected COD in the sample. 1. Add 2 ml of sample water to the COD vial. 2. Add 2 ml of deionized water is to another COD vial. This is the blank. 3. Tightly cap the vials and place them in the COD reactor at 150 °C for 2 hours. 4. Remove the vials and let them cool down to room temperature. 5. Place the vials in the spectrophotometer, which includes calibration curves either for low range or for high range. 6. Read the COD vials: first, the blank is placed and zeroed. Then, the sample can be read. Results are expressed in mg/l COD.

The amount of green colour formed is proportional to the COD of the sample. This is valid for the high range 150 to 1 500 mg/l. For the low range COD (0 to 150 mg/l) the amount of Cr^{6+} remaining is determined. After the digestion, a spectrophotometer is used to determine the COD. The spectrophotometer is set at 420 nm for the low range COD and at 620 nm for the high range COD. Chloride above 2 000 mg/l in the water sample will interfere with the results. Samples with higher concentrations should be diluted.

3.3.5 Comparison of BOD and COD

The BOD and COD values in water and wastewater differ because the two methods measure different materials:

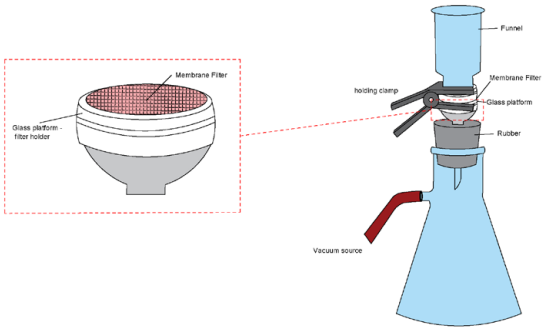
1. Many compounds that can be chemically oxidized cannot be biochemically oxidized such as lignin or cellulose.
2. The BOD test can give low values because of poor seeding materials. The COD does not require any inoculum.
3. Some toxic materials in water and wastewater may affect BOD but do not interfere with COD.
4. Usually, the COD values of contaminated water is higher than the BOD values (COD ≥ BOD).

3.3.6 Membrane filter method for analysis

The membrane filter technique is an accepted and approved procedure for testing the microbial quality of drinking water in many countries.

The method involves filtering water samples through a sterile filter (0.45 µm pore size), which is small enough to retain microorganisms. By using this technique, the water sample is passed through a membrane using a filter funnel and vacuum system. Microorganisms present in the sample will be concentrated on the filter. The filter is then incubated on a selective medium that facilitates the growth of microorganism to form colonies. Results are expressed as colony-forming unit (each visible colony, or CFU) per volume.

Figure 20. Image of the membrane filter device



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Total coliform bacteria and *Escherichia coli*

Three groups are considered as indicators of the water quality: total coliform, faecal coliform and *E. coli*. Testing for total coliform bacteria in water is the most common way to determine if there is bacterial contamination, since they provide an overview of the sanitary condition of the water supply. Most coliforms do not cause any harm; however, some strains such as *Escherichia coli* (*E. coli*) could cause illnesses.

The total coliform group is the largest group that is made up of different kinds of bacteria. Faecal coliforms are a type of total coliform that are found in feces, while *E. coli* is a sub-group of faecal coliforms. If coliform bacteria are detected in the water sample, the risk of developing water-borne illnesses increases. Positive total coliforms, especially *E. coli* should be considered an indication of faecal pollution in the water.

The maximum acceptable concentration for drinking water is assumed as nondetectable per 100 ml. This means there should be no total coliforms or *E. coli* detected to consider the water potable. The maximum acceptable concentration of *E. coli* detected in irrigation water varies, on average, between 10 and 120 *E. coli* CFU per 100 ml. The WHO set a limit for faecal coliform bacteria that is less or equal to 1 000 faecal coliform bacteria CFU per 100 ml in unrestricted irrigation.

It is recommended that restricted irrigation should have equal or less than 100 000 faecal coliform bacteria CFU per 100 ml when adult workers are exposed to spray irrigation. A limit of 1 000 faecal coliform bacteria CFU per 100 ml is recommended if children are exposed or flood irrigation is the method used.

Salmonella

Since total coliform bacteria in water give an overview of the sanitary condition of water supply, when coliform microorganisms are observed, the contamination by other species of bacteria of aecal origin that may be pathogenic is likely. Such bacterium is salmonella. Salmonella is a large contributor of foodborne diseases, and its presence in water is worrying and is the cause of many outbreaks. Irrigation water is a high vehicle

Table 11. Materials and equipment to detect salmonella in water samples

List of required materials and equipment	
Membrane filter device (funnel, glass platform, base, rubber, vacuum source)	Re-useable bottles for media (autoclave proof)
Measuring cylinders (100 and 250 ml)	Membrane filter (0.45 µm pore size)
Incubator	Sterile petri dishes
Weighing boats (100 ml)	Sterile pipettes (1 ml and 10 ml) and bulbs
Water bath	Balance
Autoclave	Hot plate
Balance	Magnetic stirrers (x2)
Distilled water (at least 3 litres)	Forceps
10 ml glass test tubes (autoclave proof)	RAPID' *E. coli* 2 medium
Spatula	RAPID' Salmonella medium
Buffered peptone water	

Source: Elaborated from standard provided by the America University of Beirut.

of bacterial transmission, for instance through the contamination of agriculture products due to contaminated irrigation water. Table 11 contains the the materials required to detect salmonella in irrigation water samples.

3.3.7 Membrane filter technique procedure

All the steps of the procedure for microbiological analysis of water samples are performed under aseptic conditions:

- A sample of 100 ml of water is collected in a sterile tube.
- The samples are kept refrigerated at 4 °C until they are needed. They should be processed the same day.
- The necessary amount of RAPID' *E. coli* 2 Medium is prepared and buffered peptone water is sterilized if any dilutions are necessary. If testing is for Salmonella, RAPID' Salmonella Medium is prepared. Any necessary dilutions are made, as described in Table 12.
- The membrane filter device (funnel, glass platform, base, rubber, vacuum source) is set up. An example is provided in Figure 20.
- Forceps are flamed and the membrane filter is placed onto the funnel of the membrane filter device.
- The sample is poured into the funnel (making sure the pouring lip of the container is flamed first).
- The vacuum is turned on and the whole sample is allowed to pass through the filter slowly.
- The funnel is rinsed with sterile water and all the liquid is allowed to pass through the filter.
- The forceps are flamed and the membrane filter is removed from the funnel.

Figure 21. Glass platform to hold membrane filters

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- The membrane filter is placed onto the petri dishes of RAPID' *E. coli* 2 Agar, incubated at 37 °C for 18-24 hours, and the results are reported. Coliforms other than *E. coli* form blue-green colonies while *E. coli* form pink to violet colonies.
- If testing for Salmonella, incubation is done at 37 °C for 18-24 hours the results are reported. Salmonella species will appear magenta.

Recommended sample volumes shown in Table 12 should be followed to reach reliable results. The volumes are defined as per the purposes of the water use and water source types.

The following protocol is recommended for the preparation of RAPID' *E. coli* 2 medium:

- 37 g of RAPID' *E. coli* 2 powder is dissolved in 1 litre of distilled water in order to prepare 1 litre of RAPID' *E. coli* 2 agar. It is important to note that 1 litre of RAPID' *E. coli* 2 will make about 30 to 36 petri dishes (90 mm x 15 mm). The weight of RAPID' *E. coli* 2 powder used should be adjusted to the amount necessary for the test.
- The appropriate amount of distilled water is measured by using a measuring cylinder.

- The appropriate amount of RAPID' *E. coli* 2 powder is weighted into the weighing boat.
- The distilled water is added into the autoclave proof bottle along with the RAPID' *E. coli* 2 powder.
- The magnetic stirrer is added into the autoclave proof bottle.
- The bottle is placed on the hot plate and mixed until the mixture becomes homogenous, and the powder is completely dissolved and boiling.
- Autoclavation is done at 121 °C for 15 minutes.
- Cooling in a water bath that is set at 55 °C is done. The bottle should not be removed until the media cools down to the desired temperature of 55 °C.
- The medium is poured into sterile petri dishes under aseptic conditions and let them dry.

The following protocol is recommended for the preparation of RAPID' Salmonella medium:

- 43.5 g of RAPID' Salmonella powder and 1 litre of distilled water are dissolved in order to prepare 1 litre of RAPID' Salmonella agar. It is important to note that 1 litre of RAPID' Salmonella will make about 30-36 petri dishes (90 mm x 15 mm). The weight of RAPID' Salmonella powder used should be adjusted to the amount necessary for the experiment.
- The appropriate amount of distilled water is measured by using a measuring cylinder.
- The appropriate amount of RAPID' Salmonella powder is weighted into the weighing boat.
- The distilled water is added into the autoclave proof bottle along with the RAPID' Salmonella powder.
- The magnetic stirrer is added into the autoclave proof bottle.

Table 12. Recommended sample volumes for membrane filtration analysis according to the sample type

Sample type	Recommended sample volume (ml)
Treated drinking water	100
Partially treated drinking water	10 and 100
Recreational water	1 and 0.1
Protected source water	10 and 1
Surface water	1 and 0.1
Wastewater	1, 0.1, and 0.01
Discharge from sewage treatment plant	1, 0.1, and 0.01
Ponds, rivers, storm water runoff	0.1, 0.01, and 0.001
Raw sewage	0.1, 0.01, and 0.001

Source: Elaborated by the America University of Beirut from standard provided.

- The bottle is placed onto the hot plate and mixed until the mixture becomes homogenous and the powder is completely dissolved and boils.
- Autoclavation is done at 121 °C for 15 minutes.
- Cooling in a water bath that is set at 55 °C is done. The bottle should not be removed until the media cools down to the desired temperature of 55 °C.
- The medium is poured into sterile petri dishes under aseptic conditions and let them dry.

The following protocol is recommended for the preparation of sterile buffered peptone water:

- 20 g of powder is dissolved in 1 litre of distilled water in order to prepare 1 litre of buffered peptone water. The weight of buffered peptone water powder used should be adjusted to the amount necessary for the experiment. Each test tube used will need 9 ml.
- The appropriate amount of distilled water is measured by using a graduated cylinder.
- The appropriate amount of buffered peptone water powder is weighted into the weighing boat.
- The distilled water is added into the autoclave proof bottle along with the buffered peptone water powder.
- The magnetic stirrer is added into the autoclave proof bottle.
- The bottle is placed onto the hot plate and mixed until the mixture becomes homogenous and the powder is completely dissolved and boiling.
- Distribution into final containers (9 ml in glass tubes in this case) is done by using 10 ml pipettes.
- Autoclavation is done at 121 °C for 15 minutes.
- The test tubes are let to cool down before they are used

4. Case study of El-Bared irrigation system

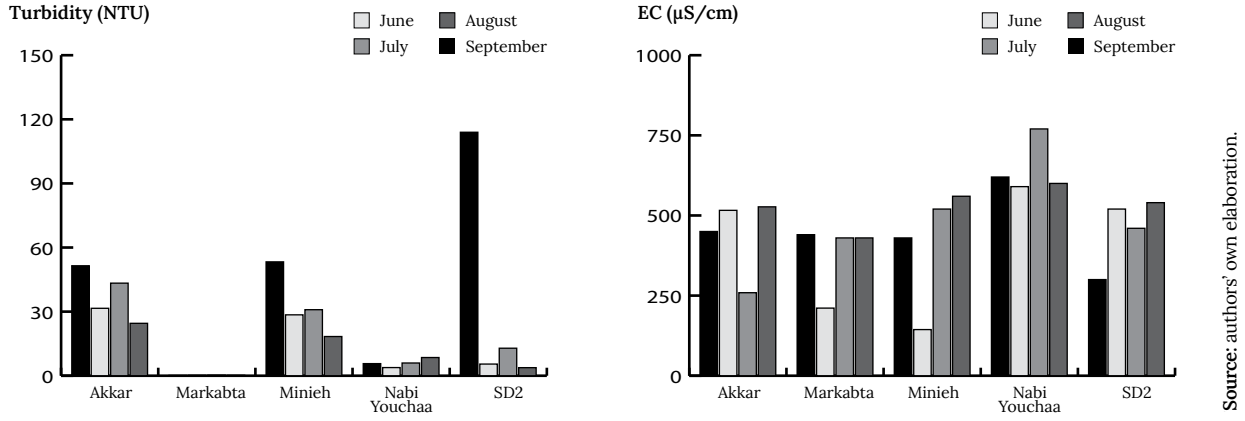
The irrigation schemes sourced from El-Bared dam are the sterling examples of why regular water quality monitoring is a hard condition of high-performing agricultural water management. Water resources are under multiple pressure of urban and industrial activities. The established water monitoring system enables a high-frequency analysis, monthly sampling in dry season and bi-monthly sampling in wet season. The overview of the analysed parameters highlights the intervention need in the area.

Physical parameters are shown in Figure 22. The turbidity is higher than acceptable rate, but the values are not consistently high. Such temporary deviation cannot be suspected as risk to the water resources or production. The conductivity values of the surface water are below the threshold, thus indicating good water quality for irrigation.

Chemical parameters results are shown in Figure 23. They do not raise major concerns, and it can be concluded that the current water quality is suitable for irrigation. Only the sodium carbonate values are consistently above the 200 mg/l threshold, which indicates a certain water hardness. However, major crop damage cannot be assumed at this level. Neither the chemical parameters nor the two biological parameters of BOD and COD pose severe threat to the production.

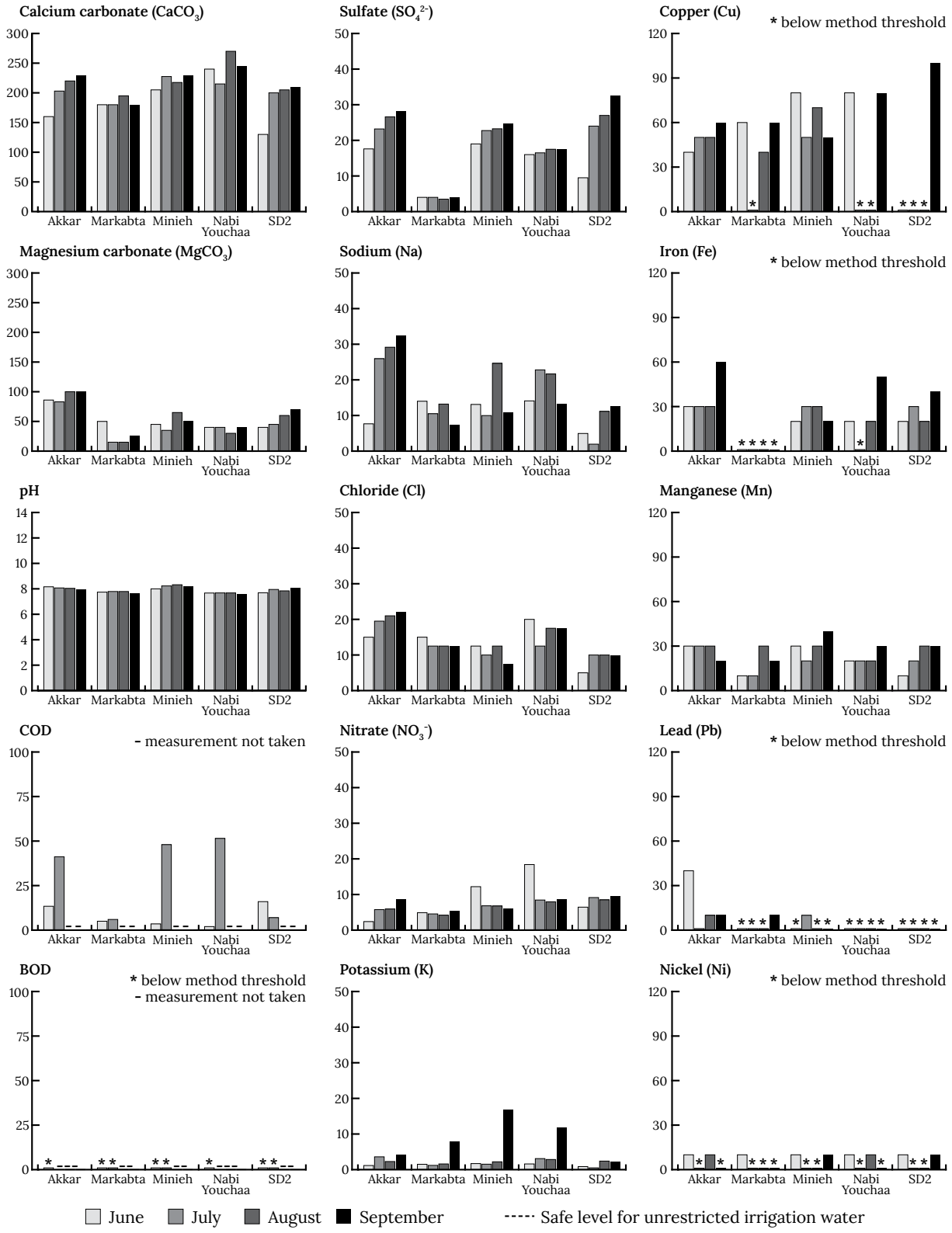
The biological analysis, however, reveals an alerting situation, as shwon in Figure 24. The measured values greatly exceed the acceptable threshold along the canal system. The two groundwater sources, Markabta and Nabi Youchaa, show the self-evident contrast to the status of surface water.

Figure 22. Results of physical analysis from irrigation water sourced from El-Bared dam



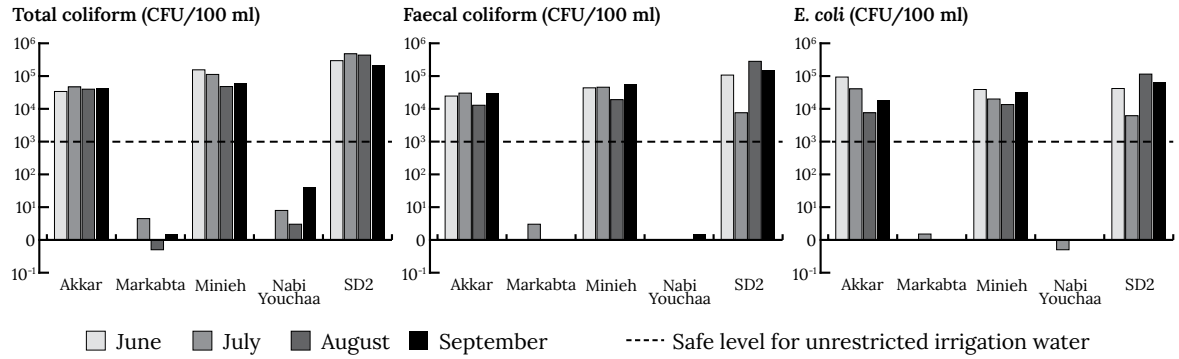
Source: authors' own elaboration.

Figure 23. Results of chemical analysis from irrigation water sourced from El-Bared dam



Source: authors' own elaboration.

Figure 24. Results of biological analysis from irrigation water sourced from El-Bared dam



Source: authors' own elaboration.

The uncontrolled sewage discharge and solid waste disposal have irreversible impact on the irrigation water. The biological contamination strains the water use for irrigation, because leafy vegetables and fruits are at direct risk of polluted water. Furthermore, such water quality requires additional safety measures for irrigators.

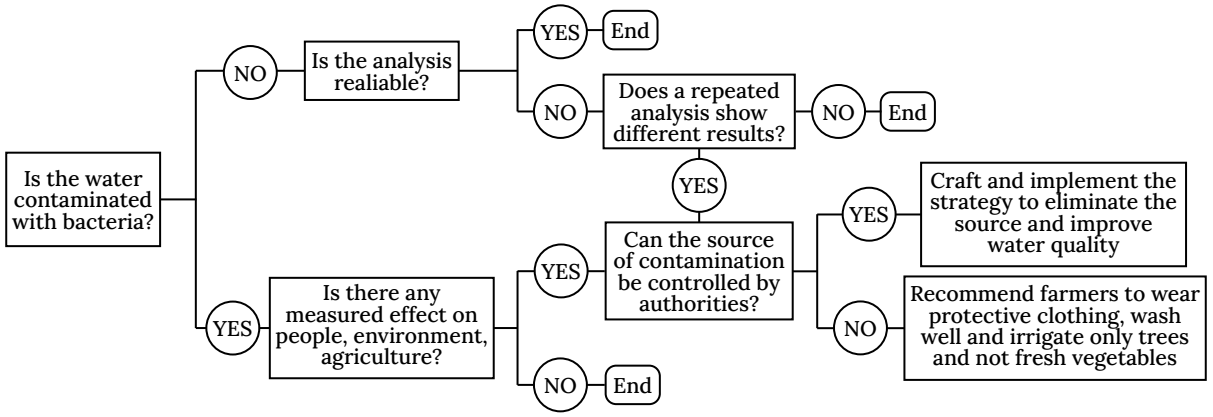
Water monitoring without follow-up action is not sufficient to avoid harmful consequences. The crafted water management strategies should take account of the identified issues and use mitigation measures to lower the risk of water quality deterioration. Decision-support trees are effective tools to identify the intervention pathways.

The first step should ascertain that the analysis results are reliable, and no error occurred during the process. If the repeated analysis confirms good water quality, regular monitoring is sufficient to maintain the recorded history.

If the analysis proves adverse trends that have impact on human, environment or agriculture, appropriate strategies should be established. The measures to be taken are conditional upon the detectable sources of pollution and the ability to eliminate these sources. The optimal case, arguably, is the prevention of water quality deterioration, and all long-term strategies should prefer sustainable solutions over the ad hoc interventions. However, it is well-understood that water quality deterioration is not a one-time event, while it has immediate impacts.

The irrigation systems in El-Bared are no exception, and the underlying structural problems are the root causes. Such problems are the lack of treatment facilities, poor connection to existing facilities and urban encroachment. However, impacts can be mitigated through temporary additional measures, such as the suspension of fresh vegetable production and protective clothes.

Figure 25. Decision tree for intervention pathways regarding irrigation water quality



Source: authors' own elaboration.

5. Conclusions

In the light of climate change and ecosystem degradation, monitoring of irrigation water quality is coming to the forefront. Growing water scarcity faces the semi-arid and arid countries, and a more cautious management of water resources is required to overcome the entailed challenges. Monitoring of irrigation water quality is fundamental to protecting water resources and maintaining agricultural production.

The oft-cited role of agriculture in water quality deterioration is, however, only one side of the equation. Agriculture, in return, sustains the damages of poor water quality, and all too often, becomes a self-inducing spiral. Yet most irrigation systems have no recorded history of water quality.

The rigorous assessment of water quality entails a complex and systematic analysis of defined quality parameters, which starts with the proper identification sites, throughout the analysis process to the informed strategy-making.

This guide is an attempt to navigate through the maze of water quality monitoring by offering practical recommendations. It is an evidence-based document that evolved through the project implementation of "Improved Water Resources Monitoring System/Integrated Water Resources Management at regional level in Lebanon" funded by the Swiss Government.

While the varying contexts of irrigation systems require different design and implementation pathways of water quality monitoring, the core protocol on sampling, analysis and interpretation of the key parameters is a guidance for all practitioners.

The tested analysis methods critically respond to the emerging problem of water quality deterioration around the globe, and they highlight the potential pitfalls of implementing monitoring systems.

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Annex

Table A1. Turbidity results (NTU)

Site	June	July	August	September
Akkar	51.47	31.56	43.33	24.53
Markbata	0.17	0.23	0.29	0.23
Minieh	53.30	28.50	30.90	18.35
Nabi Youchaa	5.67	3.82	5.96	8.52
SD2	113.95	5.46	12.88	3.78

Table A2. Electrical conductivity (µS/cm)

Site	June	July	August	September
Akkar	450	516	259	527
Markbata	440	211	430	430
Minieh	430	144	520	560
Nabi Youchaa	620	590	770	600
SD2	300	520	460	540

Table A3. Calcium carbonate ($CaCO_3$), mg/l

Site	June	July	August	September
Akkar	160.0	203.0	220.0	229.0
Markbata	180.0	180.0	195.0	180.0
Minieh	205.0	227.5	217.5	230.0
Nabi Youchaa	240.0	215.0	270.0	245.0
SD2	130.0	200.0	205.0	210.0

Table A4. Magnesium carbonate ($MgCO_3$), mg/l

Site	June	July	August	September
Akkar	86.0	83.0	100.0	100.0
Markbata	50.0	15.0	15.0	25.0
Minieh	45.0	35.0	65.0	50.0
Nabi Youchaa	40.0	40.0	30.0	40.0
SD2	40.0	45.0	60.0	70.0

Table A5. pH analysis, pH

Site	June	July	August	September
Akkar	8.16	8.07	8.04	7.94
Markbata	7.74	7.79	7.79	7.64
Minieh	8.00	8.26	8.32	8.18
Nabi Youchaa	7.67	7.68	7.68	7.62
SD2	7.69	7.95	7.84	8.06

Table A6. Chemical oxygen demand (COD), mg/l

Site	June	July	August	September
Akkar	13.4	41.2	-	-
Markbata	5.0	6.0	-	-
Minieh	3.5	48.0	-	-
Nabi Youchaa	2.0	51.5	-	-
SD2	16.0	7.0	-	-

Table A7. Biological oxygen demand (BOD), mg/l

Site	June	July	August	September
Akkar	<15	-	-	-
Markbata	<15	<15	-	-
Minieh	<15	<15	-	-
Nabi Youchaa	<15	-	-	-
SD2	<15	<15	-	-

Table A8. Sulfate (SO_4^{2-}), mg/l

Site	June	July	August	September
Akkar	17.60	23.20	26.60	28.20
Markbata	4.00	4.00	3.50	4.00
Minieh	19.00	22.75	23.25	24.75
Nabi Youchaa	16.00	16.50	17.50	17.50
SD2	9.50	24.00	27.00	32.50

Table A9. Sodium (Na), mg/l

Site	June	July	August	September
Akkar	7.66	25.94	29.16	32.42
Markbata	14.00	10.50	13.20	7.40
Minieh	13.10	9.98	24.63	10.78
Nabi Youchaa	14.10	22.80	21.65	13.20
SD2	4.95	1.95	11.15	12.45

Table A10. Chloride (Cl^-), mg/l

Site	June	July	August	September
Akkar	15.00	19.50	21.00	22.00
Markbata	15.00	12.50	12.50	12.50
Minieh	12.50	10.00	12.50	7.50
Nabi Youchaa	20.00	12.50	17.50	17.50
SD2	5.00	10.00	10.00	10.00

Table A11. Nitrate (NO_3^-), mg/l

Site	June	July	August	September
Akkar	2.40	5.76	5.93	8.68
Markbata	4.90	4.55	4.20	5.40
Minieh	12.20	6.83	6.78	6.10
Nabi Youchaa	18.40	8.45	7.95	8.70
SD2	6.45	9.15	8.50	9.40

Table A12. Potassium (K), mg/l

Site	June	July	August	September
Akkar	1.16	3.60	2.28	4.22
Markbata	1.50	1.20	1.60	8.00
Minieh	1.70	1.53	2.20	16.95
Nabi Youchaa	1.60	3.10	2.85	11.90
SD2	0.85	0.30	2.40	2.25

Table A13. Copper (Cu), µg/l

Site	June	July	August	September
Akkar	40	50	50	60
Markbata	60	10	40	60
Minieh	80	50	70	50
Nabi Youchaa	80	30	<40	80
SD2	20	<40	<40	100

Table A14. Iron (Fe), µg/l

Site	June	July	August	September
Akkar	30	30	30	60
Markbata	10	<20	<20	<20
Minieh	20	30	30	20
Nabi Youchaa	20	<20	20	50
SD2	20	30	20	40

Table A15. Manganese (Mn), µg/l

Site	June	July	August	September
Akkar	30	30	30	20
Markbata	10	10	30	20
Minieh	30	20	30	40
Nabi Youchaa	20	20	20	30
SD2	10	20	30	30

Table A16. Lead (Pb), µg/l

Site	June	July	August	September
Akkar	40	<5	10	10
Markbata	<5	<5	<5	10
Minieh	<5	10	<5	<5
Nabi Youchaa	<5	<5	<5	<5
SD2	<5	<5	<5	<5

Table A17. Nickel (Ni), µg/l

Site	June	July	August	September
Akkar	10	<7	10	<7
Markbata	10	<7	<7	<7
Minieh	10	<7	<7	10
Nabi Youchaa	10	<7	10	<7
SD2	10	<7	<7	10

Table A18. Total coliforms, CFU/100 ml

Site	June	July	August	September
Akkar	34 000	46 600	40 200	42 000
Markbata	1.0	4.5	0.5	1.5
Minieh	156 000	112 000	47 600	59 200
Nabi Youchaa	1.0	8.0	3.0	38.5
SD2	296 000	476 000	437 500	216 000

Table A19. Faecal coliform, CFU/100 ml

Site	June	July	August	September
Akkar	24 300	30 100	12 800	30 400
Markbata	0.0	3.0	0.0	1.0
Minieh	44 000	46 000	19 200	56 400
Nabi Youchaa	0.0	1.0	0.0	1.5
SD2	108 000	7 600	280 000	144 000

Table A20. *E. coli*, CFU/100 ml

Site	June	July	August	September
Akkar	93 600	41 100	7 600	17 600
Markbata	0.0	1.5	0.0	0.0
Minieh	39 000	20 000	13 600	31 600
Nabi Youchaa	0.0	0.5	0.0	0.0
SD2	42 000	6 200	115 000	64 000

Water resources are under tremendous pressure due to growing demand, climate change and anthropogenic pollution in Lebanon. Rapidly declining water quality is a key indicator of the water resources degradation that characterizes now both the freshwater and marine environment across the country.

North Lebanon is particularly dominated by a mosaic landscape. This high-degree heterogeneity makes natural resource management even more complex, and the lack of effective enforcement mechanism of environmental protection further aggravates the vulnerability of water resources.
Water quality monitoring is an essential process to enable the prevention of water resource degradation.

Good water quality improves the condition of ecosystems, thus providing healthy environment and increasing the ability to buffer climate change impacts.

This field guide builds on the acquired knowledge and experiences accumulated throughout the implementation of the "Improved water resources monitoring system - Integrated water resources management at regional level in Lebanon" project. It follows the process of evidence-based knowledge generation from the definition of problem to the sclae-out of acquired information. It is intended to be used in line with national standards and regulations.

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