Deutsch-Ukrainischer Fachdialog zur nachhaltigen Entwicklung des Obst- und Gemüsesektors

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Lehrmodule DUALOG (Skript)

MODUL OB04

Irrigation in fruit growing

Calculation of water requirements. Fertigation for apple trees

Implemented by: GFA Consulting Group, Generalbeauftragte des BMLEH Büro Berlin; ADT Project Consulting

Operational Partner Ukraine:

Introductory remarks

The transfer of practical and application-oriented knowledge and expertise is at the heart of the bilateral cooperation project "German-Ukrainian Expert Dialogue on the Sustainable Development of the Fruit and Vegetable Sector in Vinnytsia" (www.dualog-ukraine.de), which is funded by the Federal Ministry of Agriculture, Food and Rural Affairs of the Federal Republic of Germany (BMLEH).

As a key component in improving the qualifications of advisors and producers, the project implementer has produced the ***"DUALOG Teaching Modules"*** series, comprising 23 modules in German and Ukrainian. These technical guides are intended to assist advisors, specialists and producers in the fruit and vegetable sector, both in printed and digital form, as tools and reference works for advisory work and practical application. Each module explains the key aspects of the respective topic in a concise and understandable manner, thereby providing practical tips, technical know-how and experience.

In order to achieve the project's objective – improving the production and marketing of fruit and vegetables in the Vinnytsia Oblast – advising key state institutions and expanding vocational training and further education play a particularly crucial role. This series, authored by specialists with in-depth and up-to-date expertise and many years of practical experience, takes full account of this.

About the module "Irrigation in Fruit Growing"

This module presents the principles and practice of irrigation in apple orchards under Ukrainian conditions. It covers tree water physiology, soil and climate factors, irrigation system selection, scheduling methods, fertigation, system design and operation, water conservation, and economic considerations – equipping students with the knowledge to plan and manage efficient, sustainable irrigation for modern apple production.

This module describes, in a concise and practical manner, the fundamental relationships between soil, soil fertility, nutrients and fertilisation, and their effects on plant health and yield. Practical guidelines for identifying nutrient deficiencies and fertiliser requirements, as well as for the application and spreading techniques of various types of fertiliser, round off the module.

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1 Introduction

1.1 Importance of Irrigation in Apple Production

Apple (Malus domestica Borkh.) is the most economically significant pome fruit grown in Ukraine and has been a cornerstone of the country's horticultural sector for more than a century. Ukraine consistently ranks among the top ten apple-producing nations of Europe and is a leading regional exporter of fresh fruit, juice concentrate, and dried apple products. Total annual production has averaged 1.0 to 1.2 million tonnes over the past decade, drawn from an orchard area exceeding 100,000 hectares spread across all major agricultural zones from the Polissya in the north to the Black Sea steppe in the south.

Despite this importance, apple yields in Ukraine vary widely. The leading commercial orchards employing modern, high-density plantings with full irrigation regularly produce 50 to 70 tonnes per hectare, whereas older traditional orchards relying solely on natural rainfall typically yield only 10 to 25 tonnes per hectare. A large part of this gap is attributable to water management. Apple is not a drought-tolerant crop; it evolved in temperate climates where mid-summer water supply is generally adequate, and its productivity declines sharply when soil water becomes limiting during the critical fruit growth period from late May to early September.

Ukrainian growing conditions illustrate this dependence in stark terms. While the forest-steppe zone receives 500 to 600 mm of annual precipitation, the southern steppe receives only 350 to 450 mm and the distribution rarely matches crop demand. July and August evapotranspiration regularly reaches 5 to 7 mm per day, while summer rainfall is irregular and frequently delivered in short, high-intensity events that exceed the soil's infiltration capacity. Without supplementary irrigation, mid-summer water deficits of 200 to 400 mm are common in the south, and even central regions can experience yield-limiting drought episodes during years with below-normal precipitation.

Figure 1 - Major apple-growing climatic zones of Ukraine.

The bulk of commercial production is concentrated in the forest-steppe and northern steppe regions, where supplementary irrigation is increasingly essential for high-density orchards.

The role of irrigation in modern Ukrainian apple production is therefore not simply to prevent crop failure during exceptional drought years; it is an integral, season-long component of orchard management. Properly designed and operated irrigation systems allow growers to maintain the consistent soil water status that high-density orchards on dwarfing rootstocks require, to integrate nutrient management through fertigation, to manage frost risk during spring blossom periods, and to extend the productive life of the planting. Investments in irrigation infrastructure have become one of the most reliable productivity-enhancing capital expenditures for Ukrainian apple growers, with documented returns through improved fruit size, colour, sugar content, and storability.

Climate change is amplifying these considerations. Climate observations from the State Hydrometeorological Service indicate that mean summer temperatures have risen by approximately 1.5 to 2.0 °C in the south of Ukraine over the past four decades, summer precipitation has become more erratic, and the frequency of moderate to severe agricultural droughts has increased. Future projections suggest these trends will continue. Apple orchards established today are expected to remain in production for 20 to 30 years, meaning that irrigation infrastructure designed and installed in the late 2020s must perform under climate conditions that may be noticeably hotter and drier than those of the past.

1.2 Apple Tree Water Requirements Overview

A mature apple orchard transpires substantially more water than it might first appear. A vigorous bearing orchard in central Ukraine has a seasonal evapotranspiration demand of approximately 550 to 750 mm. Subtracting effective rainfall, the net irrigation requirement varies from 150 mm in wet seasons in the north to over 500 mm in dry seasons in the south. Expressed differently, a one-hectare orchard may consume between 4,000 and 7,000 cubic metres of water in a single growing season.

Water demand is not constant. It is small in early spring before leaf expansion, rises rapidly through bloom and fruit set, peaks during the long fruit expansion phase of June and July, and tapers off after harvest. Critical periods of high sensitivity to water deficit include flowering (cell division in the developing fruit), the rapid fruit growth phase of late June through early August (fruit size determination), and the four to six weeks before harvest (sugar accumulation, colour development, and finish). Even brief water stress during these periods can produce permanent losses in fruit size, yield, and quality that cannot be recovered by later irrigation.

A general guideline for Ukrainian conditions is that a mature, fully bearing orchard requires the equivalent of 4 to 6 mm of water per day during peak demand, distributed in such a way that the available soil moisture in the root zone remains above 60 percent of field capacity. The exact volume depends on rootstock, planting density, canopy size, soil type, and climate, and the irrigation system must be designed to deliver this peak demand reliably over the longest expected dry period of the season.

1.3 Objectives and Scope

This manual provides practical guidance on the design, installation, operation, and management of irrigation systems for apple production under Ukrainian conditions. It is written for orchard owners, farm managers, agronomists, extension officers, and irrigation contractors, and assumes basic familiarity with horticultural production but does not require prior knowledge of irrigation engineering.

The manual is organised in twelve chapters that move progressively from underlying principles to applied recommendations. Chapter 2 reviews apple tree physiology and water requirements. Chapters 3 and 4 examine the soil and climatic factors that determine local water needs. Chapter 5 surveys the irrigation systems most commonly used in apple production, and Chapter 6 explains how to schedule irrigation using soil-, plant-, and weather-based methods. Chapter 7 provides stage-specific water budgets, Chapter 8 covers fertigation and chemigation, and Chapter 9 deals with system design and installation. Chapter 10 addresses operation, maintenance, and troubleshooting; Chapter 11 discusses conservation and sustainability; and Chapter 12 reviews the economic dimensions. References and appendices follow.

Throughout, the focus is on practical, field-tested recommendations adapted to the Ukrainian context. Where the literature provides ranges of values, recommended defaults reflect the conditions encountered in the main commercial apple-growing zones (Vinnytsia, Khmelnytskyi, Cherkasy, Kyiv, Kharkiv, Dnipropetrovsk, Zaporizhzhia, Mykolaiv, and Kherson regions, plus the irrigated districts of the south). Conversion tables, design worksheets, and reference data are collected in the appendices for ready use in the field.

2 Apple Tree Physiology and Water Needs

Effective irrigation begins with an understanding of how the apple tree uses water. This chapter reviews the structural and functional features that determine where, when, and how much water the tree requires, and identifies the developmental stages at which water management has the greatest influence on yield and fruit quality.

2.1 Root System Structure and Depth

The depth, lateral extent, and density of the root system define the volume of soil from which an apple tree can draw water. A mature standard or semi-dwarf apple tree can develop a root system extending 1.5 to 2.5 metres below the surface and 2 to 4 metres laterally, but the great majority of fine, water-absorbing roots are concentrated in the top 30 to 60 cm of soil. As a rule of thumb, approximately 60 to 70 percent of total root mass is found within the upper 30 cm, a further 20 to 30 percent within 30 to 80 cm, and less than 10 percent below 80 cm.

Roots on dwarfing rootstocks such as M9 are shallower and less spreading than those on standard or seedling rootstocks. An M9-rooted tree in well-managed loam soil typically has its effective root zone confined to the upper 40 to 50 cm, with very few roots below one metre. This means that high-density M9 orchards are entirely dependent on the moisture status of the upper soil profile and have far less buffering capacity against short dry periods than older standard orchards. Conversely, trees on MM106, MM111, or seedling rootstocks can mine moisture from deeper layers and tolerate longer intervals between irrigations.

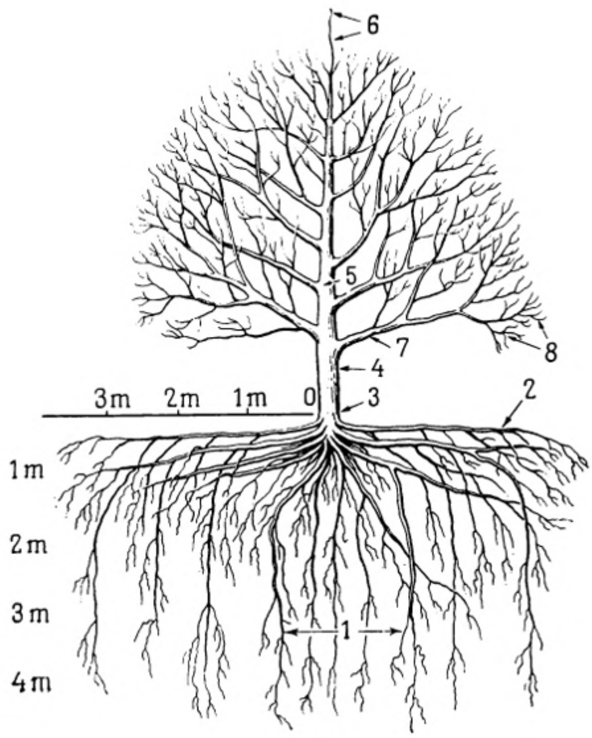


Figure 2 - Typical root architecture of a mature apple tree on a semi-dwarf rootstock.

Soil structure exerts a strong influence on root distribution. Compacted layers, clay pans, or anaerobic horizons restrict downward root growth and concentrate roots in the layers immediately above the impediment.

Stony or coarse-textured soils with poor water retention force roots to forage more widely. In Ukrainian black-earth soils (chernozems) with deep, well-drained structure, apple roots can exploit a 100 to 150 cm profile if water and nutrients are well distributed. By contrast, the heavier clay or solonetz soils of parts of the south restrict effective rooting depth to 50 to 70 cm.

The bulk of the absorbing root mass is concentrated in the upper 30 cm, with progressively fewer fine roots in deeper horizons.

Solonetz soils are characterized by a natric horizon in the subsoil which is the result of long and intense enrichment with adsorbed sodium and related texture differentiation resulting in a clay accumulation horizon with high sodium saturation (natric horizon).

From an irrigation design perspective, the effective rooting depth — the depth from which the tree extracts at least 80 percent of its water — is the critical parameter. For Ukrainian apple orchards this commonly falls in the range of 60 to 100 cm for traditional plantings and 40 to 60 cm for high-density M9 systems. Irrigation should be applied in such a way as to refill the moisture deficit of this active zone, but no deeper, since water moving below the root zone is lost.

2.2 Transpiration and Water Uptake

Water moves through the apple tree along a continuous pathway from soil, through the roots, up the xylem, into the leaves, and finally out through the stomata into the atmosphere. This flow — transpiration — is driven almost entirely by the evaporative demand of the air. On a typical bright summer day in central Ukraine, a mature apple tree of 4 metres canopy diameter can transpire 40 to 70 litres of water; under very hot, windy, dry conditions in the southern steppe this may briefly approach 100 litres per tree per day.

Stomata — the microscopic pores on the underside of leaves — regulate this flow. They open in response to light and close in response to water stress, high vapour pressure deficit, or accumulating leaf temperature. Stomatal closure during water stress is a protective response that conserves water but also halts photosynthesis and therefore stops fruit growth. Even brief midday stomatal closure during the fruit expansion period leads to measurable reductions in daily fruit weight gain.

Water uptake by the roots depends on the gradient of water potential between the soil and the root xylem. When soil water is plentiful and held loosely, uptake is easy. As the soil dries and water is held under greater suction, the tree must develop progressively lower (more negative) internal water potentials to maintain uptake. When soil suction exceeds the tree’s capacity to develop matching internal potentials, uptake stops, the leaves wilt, and photosynthesis ceases. For apple, this point — the practical wilting threshold — is reached at

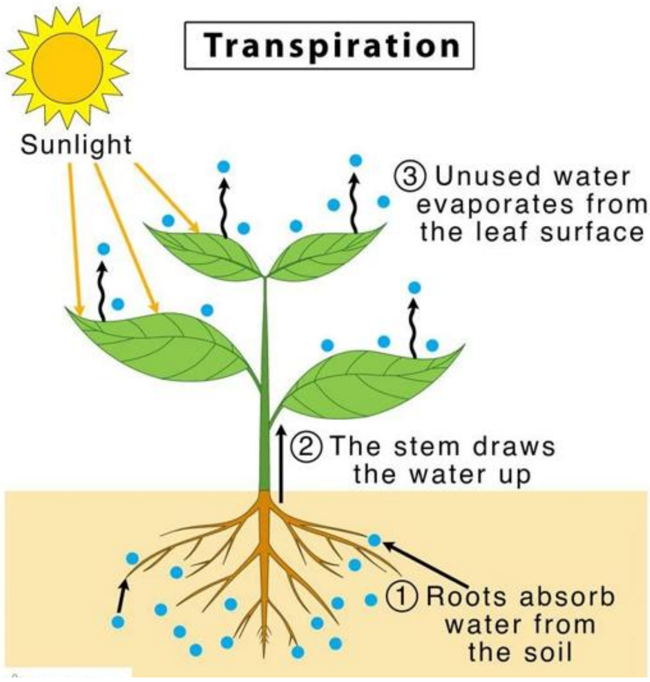


Figure 3 - Scheme: Transpiration

1.5 MPa of soil tension, although growth-limiting stress begins to manifest at much lower tensions, around 60 to 80 kPa in the active root zone.

2.3 Critical Growth Stages and Water Demand

Apple water demand varies systematically through the season, reflecting both canopy development and the changing demand of the developing crop. Figure 2.2 summarises this seasonal pattern for a mature bearing orchard.

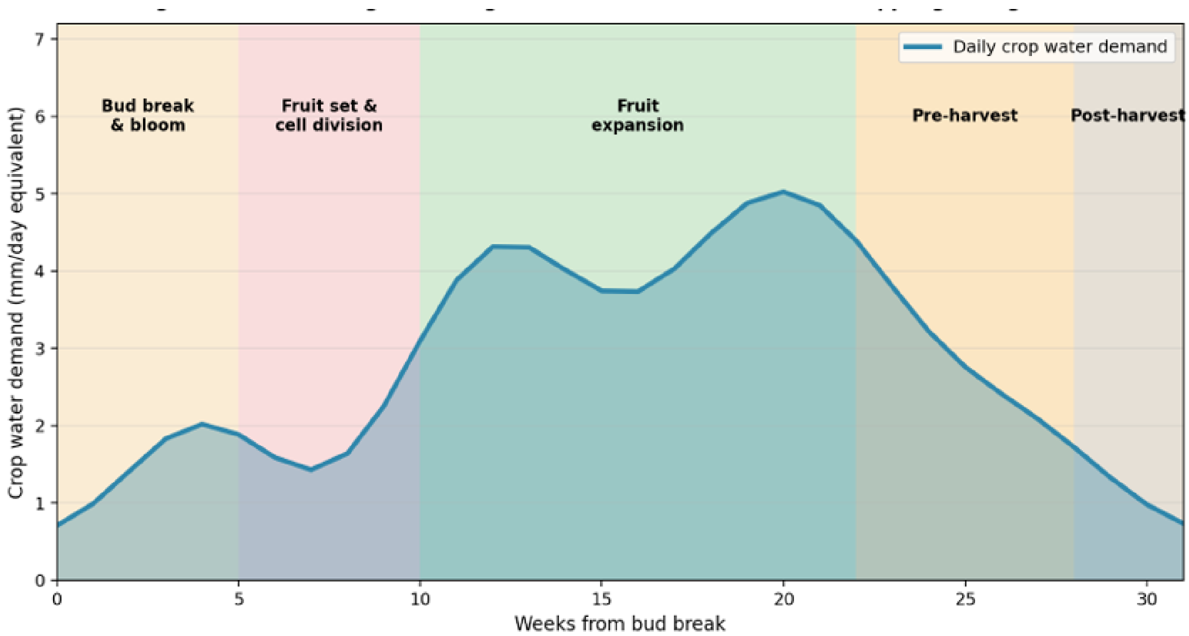


Figure 4 - Critical growth stages and approximate daily water demand across the apple growing season under central-Ukrainian conditions.

2.3.1 Bud Break and Bloom

Bud break in Ukrainian apple orchards typically occurs in late March in the south and mid-April in the north. Water demand at this stage is low — only a small leaf area has expanded — but the soil profile should be at or near field capacity going into bud break. Adequate moisture at bloom (late April to mid-May) is critical for pollen-tube growth, fertilisation, and the early phase of cell division in the developing fruitlets. Bloom-time water stress reduces fruit set and is a leading cause of poor yields in years with dry springs. In normal years, snow melt and spring rainfall supply most of this demand, but in dry springs irrigation must compensate.

Spring irrigation has the additional benefit of being available for frost protection. Overhead sprinkling during radiation frost events can protect blossoms down to approximately -4 to -5 °C through the latent heat released as the applied water freezes on the buds; this is discussed further in Chapter 5.

2.3.2 Fruit Set and Cell Division

In the three to four weeks following petal fall — typically mid-May to mid-June — the developing apple fruit undergoes its phase of cell division. The final number of cells in the fruit is set during this period, and although cell expansion can later compensate to some extent for reduced cell numbers, fruits that experience water stress during cell division never reach their full size potential. This is the single most water-sensitive stage in the apple life cycle. Soil moisture in the root zone should be maintained close to field capacity, with depletion not exceeding 30 percent of plant-available water. Application of regulated deficit strategies during this window is strongly discouraged.

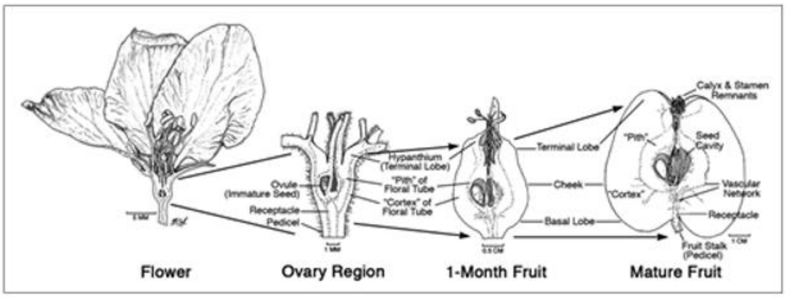


Figure 5 - Fruit development, from flower to fruit

2.4 Fruit Expansion

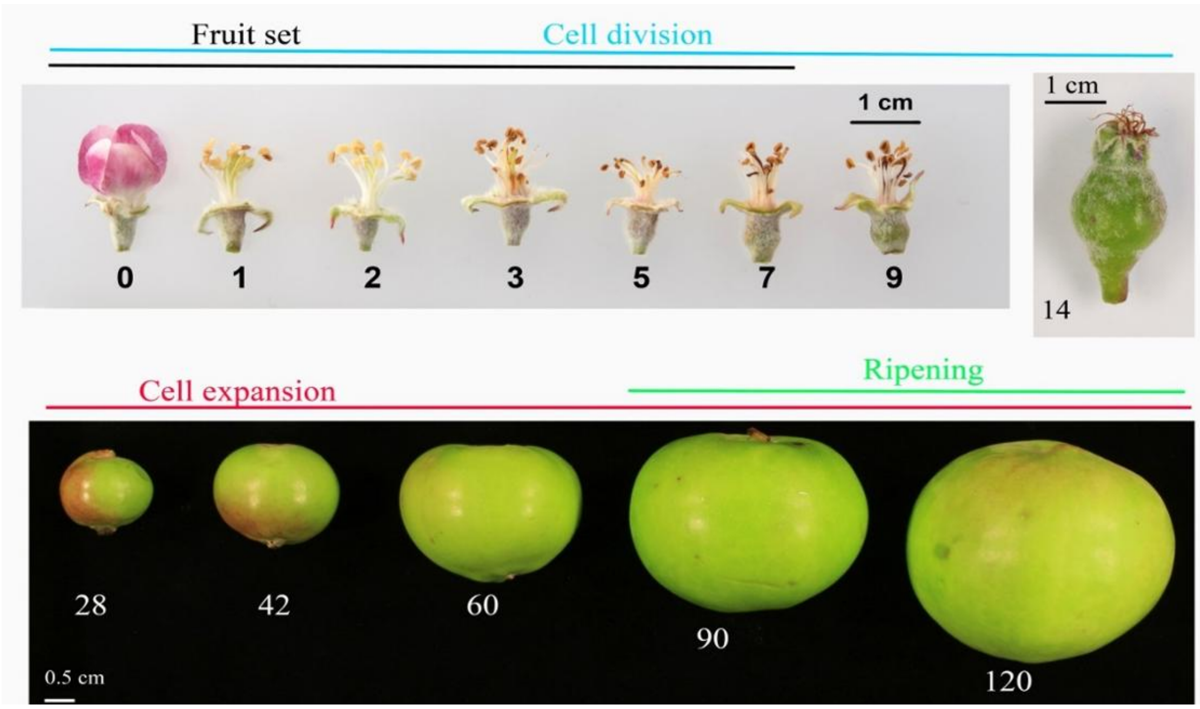


Figure 6 - Fruit Cell Division, Cell Expansion and Ripening

From approximately 30 days after petal fall until two to three weeks before harvest, the apple fruit grows almost entirely through cell expansion. This is the longest phase of the season — typically 75 to 100 days — and accounts for the great majority of the final fruit weight. Daily water demand is at its peak: 4 to 6 mm per day for a mature high-density orchard, occasionally exceeding 7 mm per day on hot, dry days in the southern steppe.

Water stress during fruit expansion directly reduces fruit size and total tonnage. Studies in apple-growing regions with similar climate to Ukraine have demonstrated that even moderate stress (50 to 60 percent of full ETc) during this phase reduces yield by 10 to 20 percent. Severe stress can also trigger premature fruit drop, cause bitter pit or other physiological disorders, and reduce the trees' carbohydrate reserves heading into autumn — which in turn weakens flower bud initiation for the following year.

For high-value cultivars destined for the fresh market, where premium prices depend on reaching minimum fruit diameter thresholds, maintaining full ETc through the fruit expansion phase is essential. Lower-value cultivars destined for juice or processing can tolerate some controlled deficit, but only during specific sub-windows of the expansion phase (see Chapter 6).

2.5 Pre-harvest and Post-harvest

In the final two to four weeks before harvest, water demand begins to decline as ETo falls and the fruit completes its expansion. Sugar accumulation, starch-to-sugar conversion, and colour development become the dominant physiological processes. Moderate water restriction at this stage can improve fruit colour, soluble solids content, and post-harvest storability, particularly for red cultivars in the Forest-Steppe zone. However, severe pre-harvest stress can cause fruit cracking (especially after a heavy rain that breaks the dry spell), and induce bitter pit by reducing calcium translocation to the fruit. The recommended strategy is therefore gentle: reduce irrigation to approximately 70 to 80 percent of ETc in the three weeks before harvest, then maintain a minimum supply.

After harvest, irrigation should continue at moderate levels (approximately 60 percent of ETc) until leaf fall, particularly in dry autumns. Post-harvest water status influences carbohydrate reserves stored in the trunk and roots, which in turn supports root growth in the autumn, winter hardiness, and the early spring flush of growth the following season. Allowing trees to enter winter under significant water deficit is a common — and avoidable — cause of weak return bloom and reduced yields.

2.6 Water Stress: Symptoms and Effects on Yield

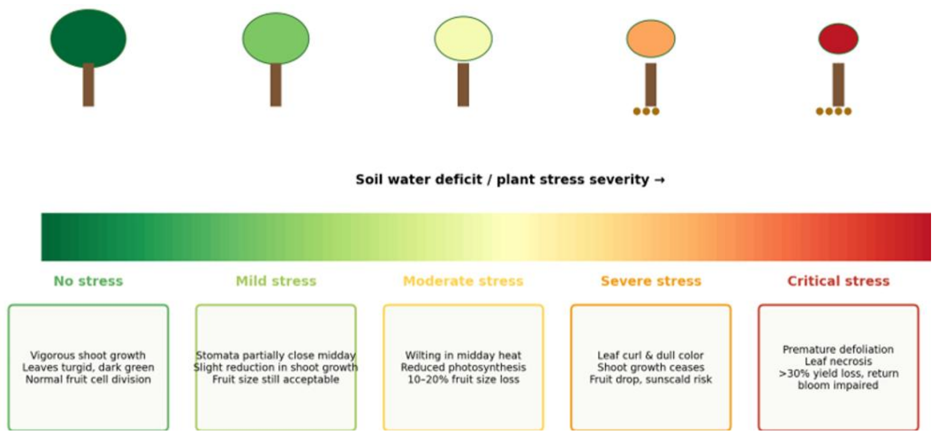


Figure 7 - Progressive symptoms of water stress in apple trees.

Early signs are often subtle and require careful observation; by the time visible wilting or leaf damage occurs, significant yield loss has already happened.

Recognising the symptoms of water stress is an essential skill for the orchard manager. Stress symptoms in apple progress through a fairly predictable sequence as soil water is depleted.

The earliest signs are subtle: a slight loss of the dark green leaf colour, a reduction in the rate of new shoot extension, and progressive midday stomatal closure that is not visible to the eye. As stress deepens, leaves begin to wilt during the hottest part of the day but recover overnight; shoot growth slows or stops; and fruit growth rate falls. Severe stress produces leaf curling, dull or grey-green colouration, and eventually premature defoliation, with permanent damage to that season's crop and weakening of next year's. Crop losses from severe stress can range from 30 percent to total crop failure.

Quantitative thresholds for the onset of yield-limiting stress in apple are well established. In the active root zone, the irrigation manager should aim to keep:

- Soil moisture above 60 percent of available water (or, equivalently, depletion below 40 percent of plant-available water);
- Soil matric tension below 40 to 60 kPa at the active root depth (10 to 30 cm for high-density M9, 30 to 50 cm for traditional orchards);
- Stem water potential at midday no more negative than -1.2 to -1.5 MPa during fruit expansion.

When any of these indicators crosses the relevant threshold, irrigation should be scheduled immediately to prevent yield loss. The use of these indicators in practical scheduling is covered in Chapter 6.

3 Soil and Site Considerations

Soil is the storage medium through which irrigation water reaches the apple tree. Its physical properties determine how much water it can hold, how quickly it accepts water, how rapidly that water drains, and how readily the tree can extract it. A clear understanding of the soil at the orchard site is therefore the foundation of any irrigation programme.

3.1 Soil Texture and Water-Holding Capacity

Soil texture — the relative proportion of sand, silt, and clay particles — controls the size and arrangement of soil pores, and hence the soil's ability to hold and release water. Coarse-textured soils (sandy soils) have large pores, drain rapidly, and hold little water; fine-textured soils (clays) have small pores, drain slowly, and hold more water, but much of it is held so tightly that the plant cannot extract it. Medium-textured soils (loams) generally offer the best compromise for apple production: moderate water-holding capacity, good drainage, and good aeration.

Most of the major apple-growing regions of Ukraine are situated on deep, well-structured chernozem (black earth) soils — silty loams or silty clay loams with excellent natural fertility, very good water-holding capacity, and stable structure. These soils can hold up to 200 mm of plant-available water per metre of depth, which makes them well-suited to apple culture. By contrast, the sandy and sandy-loam soils of parts of the Polissya zone hold only 80 to 120 mm per metre and require more frequent irrigation, while the heavy clays of some areas of Cherkasy, Kirovohrad, and the south can be slow-draining and prone to waterlogging without careful management.

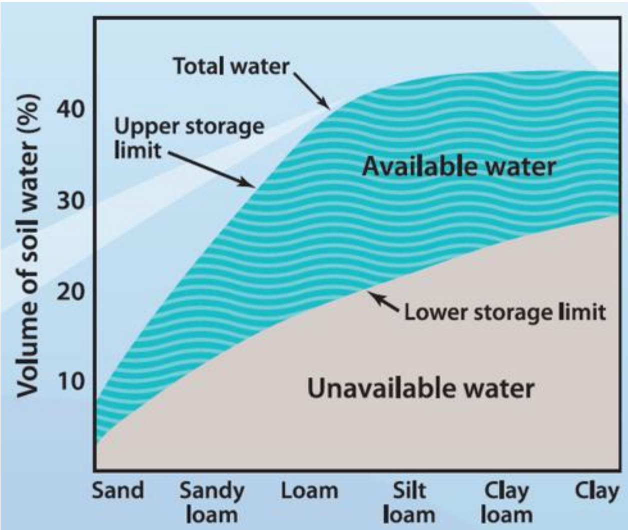


Figure 8 - Volumetric water content at saturation, field capacity (FC), and permanent wilting point (PWP) for three textural classes. The plant-available water (PAW) is the difference between FC and PWP, and represents the water the soil can supply to the tree.

3.2 Field Capacity, Wilting Point, and Available Water

Three soil-water concepts are used routinely in irrigation management:

- Saturation: All pores in the soil are filled with water. This condition is unsustainable for healthy apple roots; roots will suffocate within a few days if the soil remains saturated.
- Field capacity (FC): The water content remaining after a saturated soil has been allowed to drain freely under gravity for one to three days. This is the upper limit of the water content that is useful to the plant.

- Permanent wilting point (PWP): The water content at which the plant can no longer extract water from the soil and wilts permanently. For most practical purposes this is taken as a matric tension of 1.5 MPa (15 atmospheres).

The difference between FC and PWP is the plant-available water (PAW) — the water that the apple tree can actually use. Typical PAW values are approximately 6 to 10 mm per 10 cm of soil depth in sandy soils, 15 to 18 mm per 10 cm in loams and silt loams, and 17 to 20 mm per 10 cm in silty clay loams. The PAW for the full effective root zone is the product of this value and the depth of the active root zone; for a chernozem loam supporting a mature apple tree with a 100 cm effective root depth, the PAW reservoir is therefore approximately 150 to 180 mm.

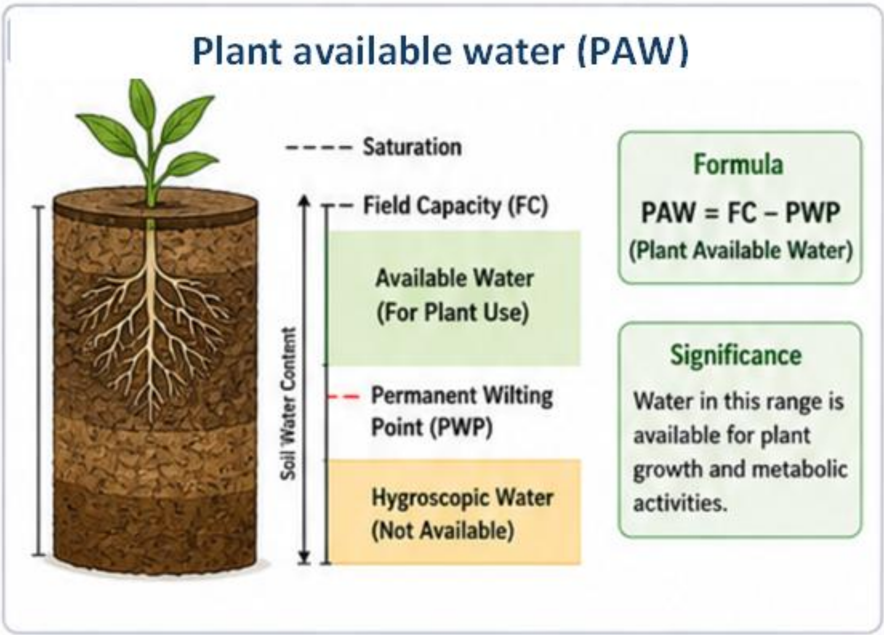


Figure 9 - Plant available water (PAW)

In irrigation practice, the goal is to refill the rooting zone to FC and then to allow the tree to extract water until a chosen fraction of PAW has been depleted, at which point the next irrigation is applied. For apple in the critical stages, this depletion fraction should not exceed 30 to 40 percent of PAW. A summary of representative values is given in Table 3.1.

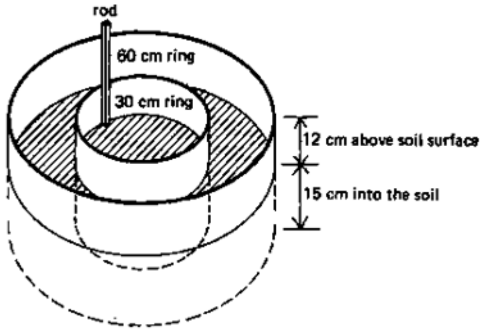
Soil texture	Field capacity (vol. %)	PWP (vol. %)	PAW (mm / 10 cm)	Typical infil. rate (mm/h)
Sand	10 – 15	3 – 5	7 – 10	> 30
Sandy loam	18 – 22	6 – 10	10 – 13	15 – 30
Loam	24 – 30	10 – 13	14 – 17	10 – 20
Silt loam (chernozem)	28 – 34	11 – 15	16 – 19	8 – 15
Clay loam	32 – 38	15 – 18	17 – 20	4 – 8
Clay	38 – 45	20 – 25	17 – 22	1 – 4

Table 1 — Representative soil-water characteristics for major textural classes encountered in Ukrainian apple orchards.

3.3 Soil Depth and Drainage

The effective rooting depth — and hence the volume of water available to the tree — is determined by both the textural profile of the soil and any layers that restrict root penetration. Common impediments in Ukrainian orchard soils include plough pans (compacted layers at the base of long-term tillage), natural clay layers, gleyed (anaerobic) horizons, and limestone or other hardpans. Before establishing an orchard, the soil profile should be examined to a depth of at least 150 cm at multiple representative locations. Soil pits dug with a backhoe are the preferred method; auger holes are an acceptable second-best.

Drainage is the other critical aspect of soil suitability. Apple trees cannot tolerate prolonged saturation of the root zone. Even short-term waterlogging during the growing season causes oxygen deprivation, root death, and increased susceptibility to phytophthora collar rot. A site that ponds water after spring snow melt or summer rainstorms is not suitable for apple without artificial drainage. Drainage requirements are typically assessed by digging a pit to 100 cm, filling it with water, and observing the drop in water level over 24 hours; satisfactory drainage corresponds to a drop of at least 50 cm in 24 hours.



The most common method to measure the infiltration rate is by a field test using a cylinder or ring infiltrometer. A ring infiltrometer typically consists of an inner cylinder of 30 cm diameter and an outer cylinder of 60 cm diameter. Instead of the outer cylinder, a bund could be made to prevent lateral water flow.

When natural drainage is inadequate, options include subsurface tile drainage at 0.8 to 1.2 m depth, mole drainage (where applicable), raised planting beds, or — as a last resort — selecting a different site. Drainage installations must be planned in conjunction with irrigation infrastructure, since flooding from an irrigation malfunction is one of the most common ways of waterlogging an otherwise well-drained orchard.

3.4 Topography and Microclimate

Topography influences both irrigation system design and the microclimate of the orchard. The principal considerations are:

- Slope: Slopes greater than 5 percent require careful design of pressurised systems to control pressure variation along laterals, and may favour pressure-compensating emitters in drip systems. Slopes greater than 8 to 10 percent are generally unsuitable for furrow irrigation due to erosion risk.
- Aspect: South- and west-facing slopes receive more direct sunlight, warm earlier in spring, and have higher evapotranspiration; they may produce earlier harvests but require correspondingly higher irrigation. North-facing slopes are cooler and may extend the growing season but warm slowly and are more frost-prone.
- Frost pockets: Low-lying areas of the orchard accumulate cold air on still spring nights and are prone to bloom-period frosts. Such sites benefit from overhead sprinkler irrigation as a frost-protection tool, and may justify the higher cost of dual-purpose installations.
- Wind exposure: Exposed sites have higher ETo, greater drift losses from sprinkler systems, and increased risk of fruit rub. Windbreaks (typically of poplar, alder, or

hornbeam) are commonly used in Ukrainian orchards and can reduce within-orchard ETo by 10 to 15 percent.

3.5 Water holding capacity of organic matter

Organic matter improves the soil's ability to hold water. When the organic matter content in the top 30 cm of soil increases by 1%, the soil can store a significant amount of extra water per hectare. The exact amount depends on the soil type and the bulk density of the soil.

In general, soils with a higher bulk density can hold more extra water for each 1% increase in organic matter. For example, light sandy soil with a bulk density of about 1.6 t/m³ can hold approximately 240,000 litres of extra water per hectare, which equals 24.0 mm of water. Sandy loam can hold about 225,000 litres per hectare, or 22.5 mm. Loam can hold about 210,000 litres per hectare, equal to 21.0 mm. Clay soil can hold about 195,000 litres per hectare, or 19.5 mm. Peat or organic soils with a low bulk density can hold about 105,000 litres per hectare, equal to 10.5 mm.

A useful conversion is that 1 mm of water on 1 hectare equals 10,000 litres per hectare. These values are typical estimates and may vary depending on field conditions, soil structure, compaction, rooting depth and the quality of the organic matter.

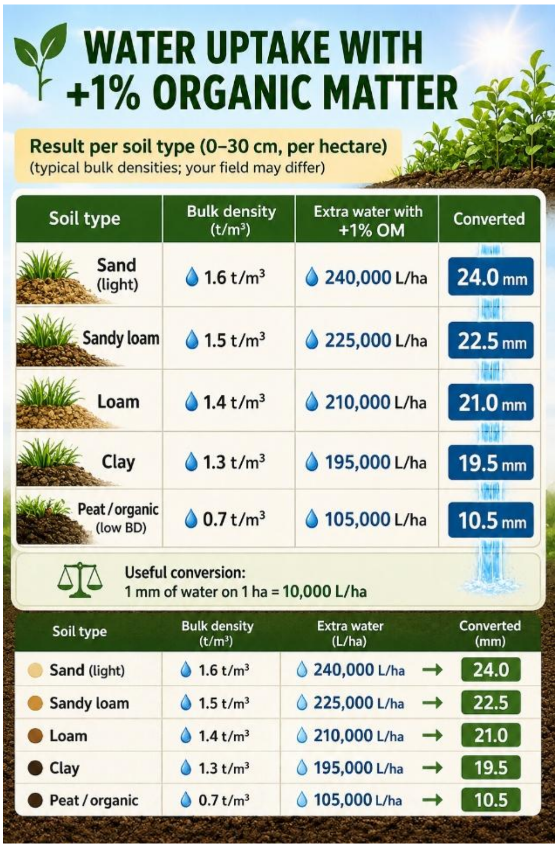


Figure 10 - water uptake of organic matter

3.6 Water Quality and Salinity

Water quality directly affects both crop performance and the longevity of the irrigation system. The principal quality parameters of concern are:

- Total dissolved solids (salinity), expressed as electrical conductivity (EC). Apple is moderately sensitive to salinity; yield reductions begin at an EC of irrigation water of approximately 1.5 dS/m, with severe damage above 2.5 to 3.0 dS/m.
- Sodium adsorption ratio (SAR), which influences soil structure. SAR values above 6 to 9, particularly combined with low salinity, can cause clay dispersion and reduced soil permeability.
- Chloride concentration. Apple is moderately sensitive to chloride; concentrations above 250 mg/L can cause leaf burn, particularly with overhead irrigation.
- Boron concentration. Apple is sensitive to boron; concentrations above 0.7 mg/L may cause toxicity.

- Suspended solids and biological load, which affect filter selection and emitter clogging risk (Chapter 9).
- pH, which affects nutrient availability and the stability of fertiliser solutions in fertigation systems.

Surface water in Ukrainian apple-growing regions is generally of good quality, with EC typically below 0.8 dS/m and low chloride and sodium concentrations. Groundwater can be more variable: shallow wells in chernozem regions tend to produce water of good quality, while deeper wells in some southern districts can yield brackish water with EC above 2 dS/m. Water from drainage canals and reused irrigation water often has elevated EC, chloride, and biological load and requires careful treatment before use on apple.

A full water analysis should be conducted before designing any irrigation system. The analysis should include EC, pH, total alkalinity, calcium, magnesium, sodium, potassium, chloride, sulphate, bicarbonate, nitrate, iron, manganese, and boron, together with suspended solids and total bacterial count. The results inform filter selection, fertiliser compatibility, and the choice of emitter type. Sources with iron above 0.2 mg/L or with high bicarbonate generally require acid injection to prevent emitter clogging from precipitates.

4 Climatic Factors Affecting Irrigation

Climate is the single most important external driver of orchard water demand. Two orchards on the same soil and with the same management may have water requirements that differ by 30 to 50 percent depending on their climatic setting. Understanding the climatic drivers — and how they combine into evapotranspiration — is the foundation of any rational irrigation schedule.

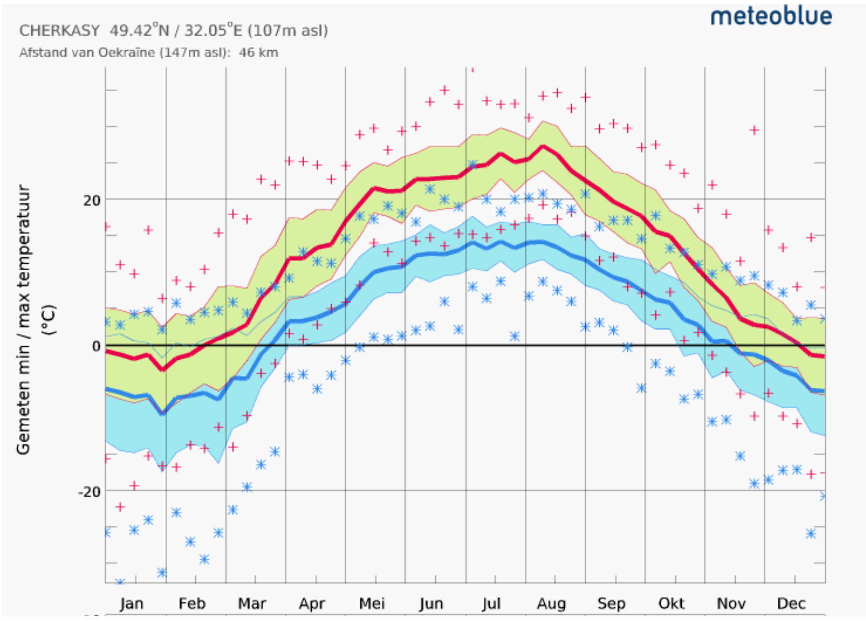


Figure 11 - Meteoblue: Temperature Ukraine

Ukrainian apple-growing regions span a wide climatic gradient, from the relatively humid sub-Carpathian zone in the west to the semi-arid steppe of Kherson and Mykolaiv. This chapter introduces the underlying concepts and provides the climatic data needed for water-balance calculations in each major region.

4.1 Evapotranspiration (ET) Concepts

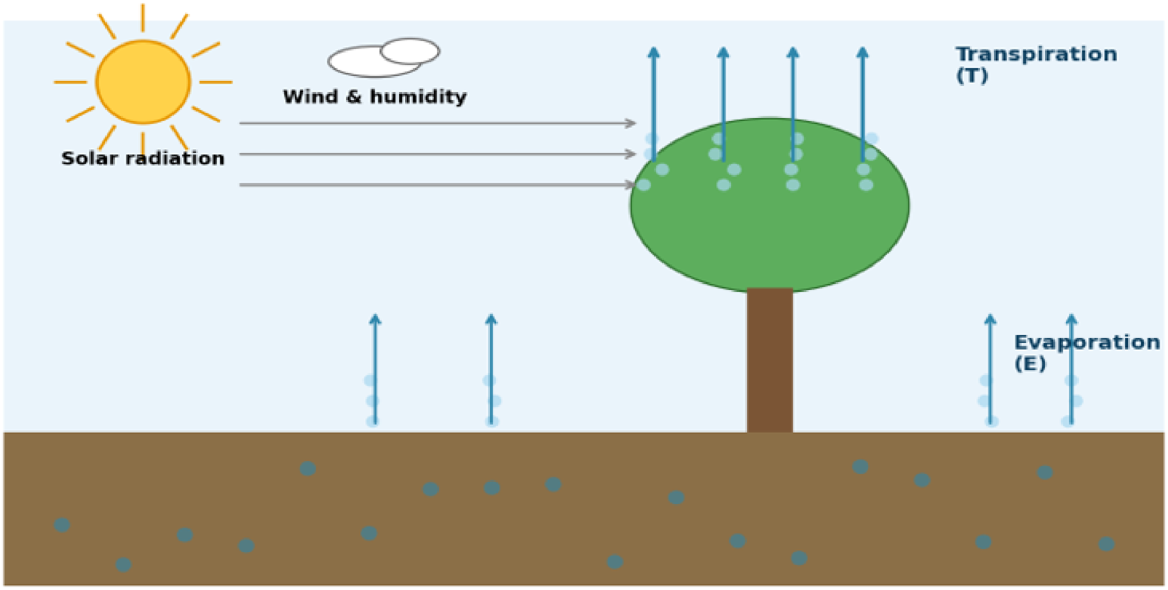
Evapotranspiration is the combined loss of water from soil evaporation and plant transpiration. It is the dominant term in the water balance of an irrigated orchard during the growing season and accounts for nearly all of the water that must be replaced by rainfall and irrigation. The simplified field water balance is:

Irrigation = Crop ET − Effective rainfall + Drainage losses − Change in soil water storage

Crop evapotranspiration (ETc) reflects the combined effect of weather, the area of leaves intercepting radiation, the size and activity of the root system, and the management of the orchard floor. It is conventionally separated into two components: reference evapotranspiration (ETo), which represents the climatic demand for water from a standard reference surface, and the crop coefficient (Kc), which adjusts ETo to the specific crop and growth stage.

A central insight of the ET approach is that water demand is set principally by the atmosphere — by radiation, temperature, humidity, and wind — rather than by the crop. The crop modulates this demand through its leaf area and physiological control of stomata, but on a clear summer day the atmospheric demand may exceed 7 mm of water per day regardless of which crop is grown. Recognizing this distinction is essential for understanding why ETo data from a single weather station serves all crops in a region, with only Kc values differing among them.

ET = T + E | ETc (crop) = ETo × Kc



The evapotranspiration concept. Atmospheric demand drives both soil evaporation (E) and plant transpiration (T); their sum (ET) is the water that must be supplied by rainfall and irrigation.

4.2 Reference ET (ETo) and Crop Coefficients (Kc)

Reference evapotranspiration (ETo) is defined as the rate of water loss from a hypothetical reference surface of well-watered, actively growing short grass of 0.12 m height with a surface resistance of 70 s/m and an albedo of 0.23. The FAO Penman-Monteith equation is the international standard for ETo calculation; it requires daily values of maximum and minimum temperature, relative humidity, wind speed at 2 m, and solar radiation. ETo is reported in millimetres per day and represents the climatic demand for water at the location and date in question.

Typical monthly ETo values for the principal apple-growing regions of Ukraine are summarised in the table below. Values are long-term averages derived from agro-meteorological stations operated by the Ukrainian Hydrometeorological Centre and from Penman-Monteith calculations on CLIMWAT and CRU climatic data.

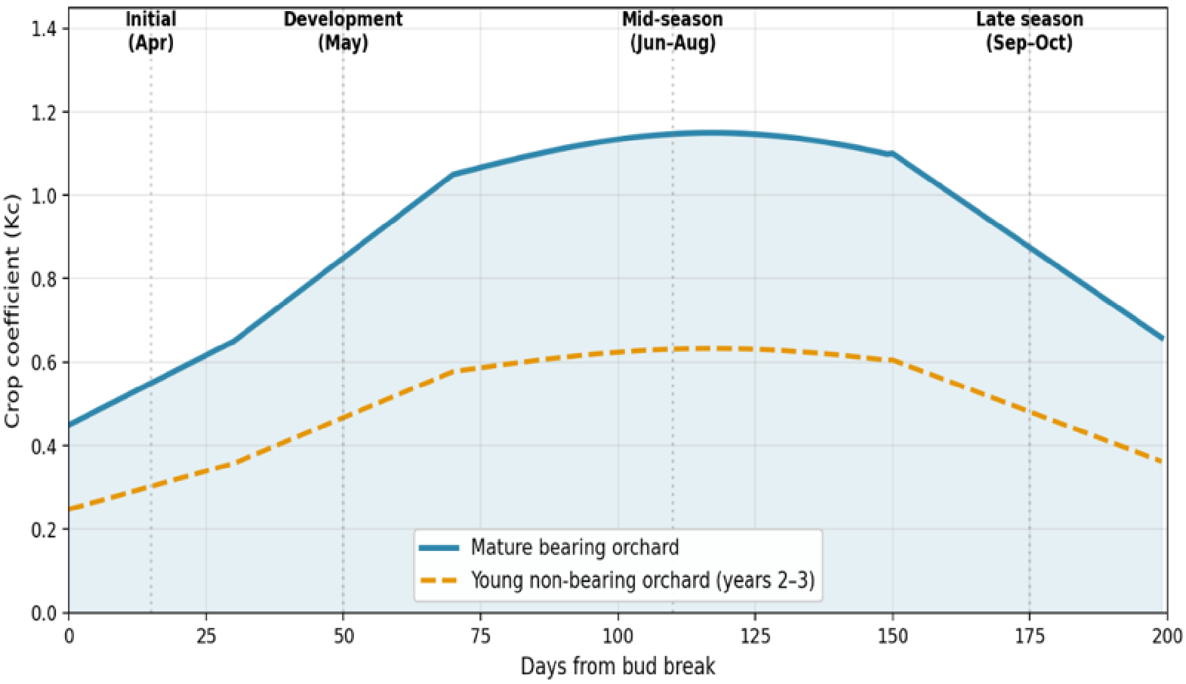
Region	Apr	May	Jun	Jul	Aug	Sep	Season
Vinnytsia (forest-steppe)	60	95	120	135	120	75	605
Kyiv (forest-steppe)	65	100	125	140	125	80	635
Kherson (steppe)	80	125	160	180	160	105	810

Mykolaiv (steppe)	75	120	155	175	155	100	780
Zakarpattia (sub-Carpathian)	55	90	110	125	110	70	560
Lviv (western)	55	85	105	120	110	70	545

Table 2 — Mean monthly reference evapotranspiration (ETo, mm) for principal Ukrainian apple-growing regions. Season totals cover April to September.

The crop coefficient (Kc) converts ETo into the actual water requirement of the orchard: ETc = Kc × ETo.

Kc captures the difference between the reference grass surface and the apple orchard. It depends on canopy development (which affects radiation interception), ground cover (bare soil, cover crop, or mulch), tree training system, and the wetting frequency of the soil surface. For a mature, full-canopy apple orchard on bare soil with daily drip irrigation, peak summer Kc values are in the range of 1.0 to 1.15. For young orchards, Kc is much lower because the leaf area is small and most of the ground is bare.



Seasonal crop coefficient (Kc) curves for a mature and a young apple orchard in central Ukraine, plotted against the orchard calendar. The curve shape reflects canopy development, full cover, and senescence stages.

Recommended Kc values by growth stage and orchard age for Ukrainian conditions are given in Table 4.2. These values assume daily or every-second-day drip irrigation and a bare or lightly mulched strip beneath the trees with a permanent grass or mowed alley. Adjustments are needed for fully grassed orchards (add 0.10 to 0.15 during periods of active grass growth) or for orchards under continuous mulch (subtract 0.05 to 0.10 to account for reduced soil evaporation).

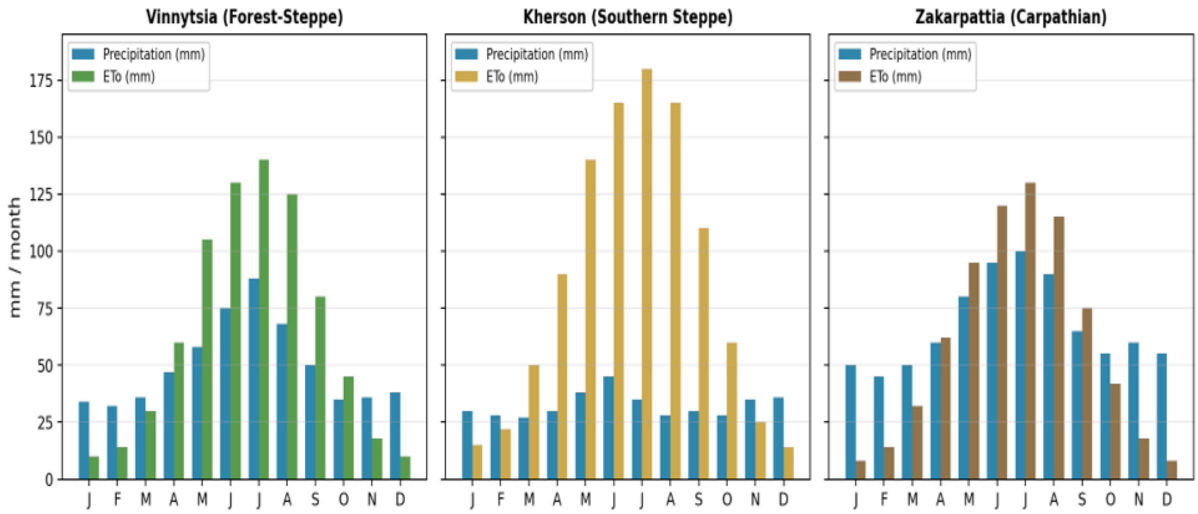
Stage	**Approx. dates**	**Kc, young (Y1–Y3)**	**Kc, semi-mature (Y4–Y6)**	**Kc, mature (Y7+)**

Bud break to bloom	Late Apr – mid May	0.35	0.55	0.70
Bloom to fruit set	Mid May – early Jun	0.45	0.70	0.85
Cell division	Early Jun – mid Jul	0.50	0.85	1.05
Cell expansion	Mid Jul – mid Aug	0.50	0.90	1.15
Pre-harvest	Mid Aug – mid Sep	0.45	0.85	1.05
Post-harvest	Mid Sep – leaf fall	0.35	0.55	0.65

Table 3 — Recommended apple crop coefficients (Kc) by growth stage and orchard age for Ukrainian conditions, drip-irrigated orchards with managed grass alleys.

4.3 Rainfall Patterns and Effective Precipitation

Rainfall is the principal source of water for most Ukrainian apple orchards and the reference against which the need for irrigation is judged. The distribution of rainfall during the growing season is at least as important as the total. Western and central regions receive moderately reliable rainfall of 550 to 700 mm per year, with about 350 to 450 mm falling between April and October. Southern regions are more variable, receiving 350 to 450 mm per year, with growing-season totals frequently below 250 mm in dry years and concentrated in a small number of intense events.



Monthly mean precipitation (bars) and reference evapotranspiration (line) for three contrasting Ukrainian apple-growing regions: Vinnytsia (forest-steppe), Kherson (steppe), and Zakarpattia (sub-Carpathian). The shaded period (May–August) is the principal irrigation season.

Not all rainfall contributes to crop water supply. The fraction that does is called effective rainfall and reflects losses to runoff, deep percolation below the root zone, and canopy interception that evaporates without reaching the soil. For apple orchards on medium-textured soils with managed grass alleys, the following empirical guidelines provide reasonable estimates of effective rainfall:

- Rainfall events of less than 5 mm: effective fraction approximately 0 to 30 percent (most evaporates from canopy and surface).
- Rainfall events of 5 to 25 mm: effective fraction approximately 70 to 90 percent.

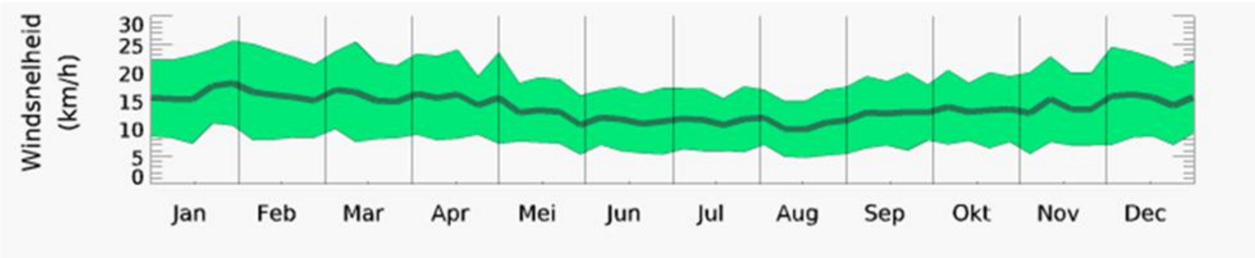
- Rainfall events of 25 to 50 mm: effective fraction approximately 80 to 90 percent.
- Rainfall events greater than 50 mm: effective fraction declines because of runoff and deep percolation; assume 60 to 75 percent.

For monthly water-balance calculations, an effective-rainfall fraction of 75 to 80 percent of monthly totals is a common approximation in Ukrainian conditions, with adjustment downward in months dominated by a few heavy rainfall events and upward in months with a steady distribution of moderate rainfalls.

Long-term records are essential to designing irrigation systems with appropriate reliability. Designing only to mean rainfall produces systems that fail in roughly half of all years. Typical design practice in commercial Ukrainian orchards is to size for a dry year corresponding to the 20th percentile of historical rainfall (a one-in-five dry year), with operational flexibility to draw extra water from storage in still drier years.

4.4 Temperature, Humidity, and Wind

Temperature is the most familiar climatic variable and the strongest driver of growing-season ETo. Each 1 °C increase in mean summer temperature increases ETo by approximately 5 to 7 percent. Daily maximum temperature drives midday peaks in transpiration; minimum temperature affects night-time recovery from water stress. Extreme high temperatures (above 32 °C) can cause stomatal closure even in well-watered trees, with a temporary suppression of transpiration that produces apparent under-use of irrigation water and risks sunscald of fruit, particularly on the south-west sides of trees.



Meteoblue Windspeed, Ukraine

Relative humidity affects ETo through its influence on the vapour pressure deficit (VPD), which is the driving gradient for transpiration. Low relative humidity (high VPD) increases transpiration demand; high humidity reduces it. Coastal and southern steppe regions of Ukraine experience low summer humidity, with afternoon VPDs frequently exceeding 3 kPa; western Ukraine and the Carpathian foothills have markedly higher humidity and correspondingly lower transpiration demand for the same temperature.

Wind enhances both evaporation from soil and transpiration from canopies by carrying away the boundary layer of saturated air around leaves and the soil surface. Wind speeds of 2 to 3 m/s at 2 m height (typical of open agricultural sites) are assumed in standard ETo calculations; values of 5 to 7 m/s — common in the steppe — increase ETo by 10 to 20 percent and are an important driver of irrigation demand. Strong winds also reduce the efficiency of overhead and sprinkler irrigation through drift and evaporative losses and may make microsprinkler systems unsuitable.

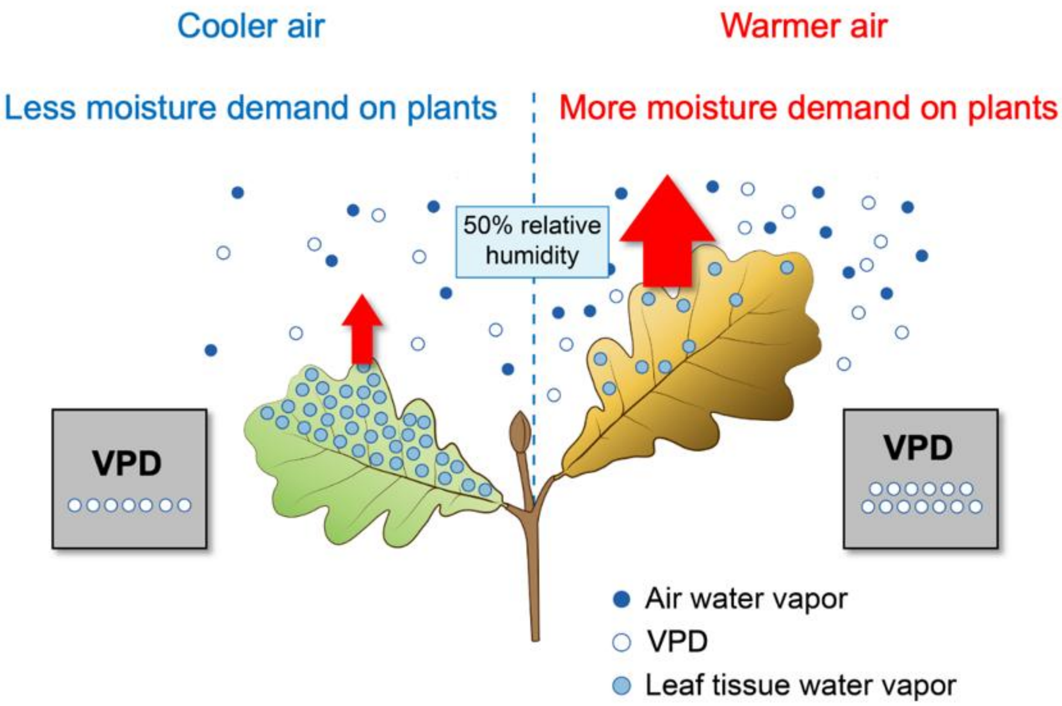
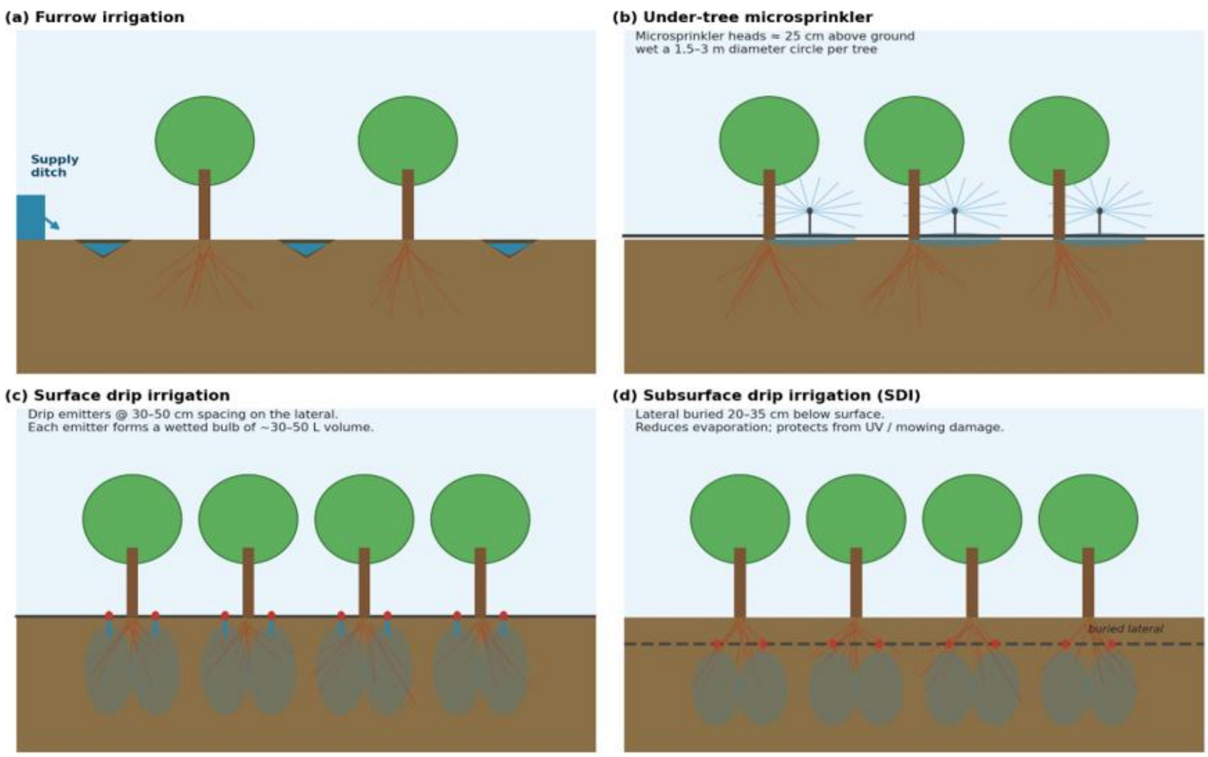


Figure 12 - Vapour Pressure Deficit (VPD)

5 Irrigation Systems for Apple Orchards

Several distinct technologies exist for delivering water to apple orchards. Each has characteristic strengths, limitations, capital and operating costs, and is best suited to a particular combination of soil, topography, water source, and orchard design. This chapter describes the principal systems used in Ukrainian apple production, with particular emphasis on the choice between surface, sprinkler, and drip irrigation that confronts most growers planning a new installation.

Figure 5.1 — Common irrigation systems used in apple orchards



Schematic comparison of four irrigation systems used in apple orchards: (a) furrow irrigation, (b) microsprinkler, (c) surface drip, (d) subsurface drip irrigation (SDI). System choice influences water-use efficiency, capital cost, labour requirement, and suitability for fertigation.

5.1 Surface Irrigation (Furrow, Basin)

Surface irrigation distributes water across the orchard floor by gravity, either in furrows running parallel to tree rows or in basins surrounding each tree or group of trees. It is the oldest method, dominant historically in the southern steppe regions of Ukraine, and is still found in older orchards on suitable soils. Its principal attractions are low capital cost, simple equipment, and freedom from the energy demands of pumping under pressure.

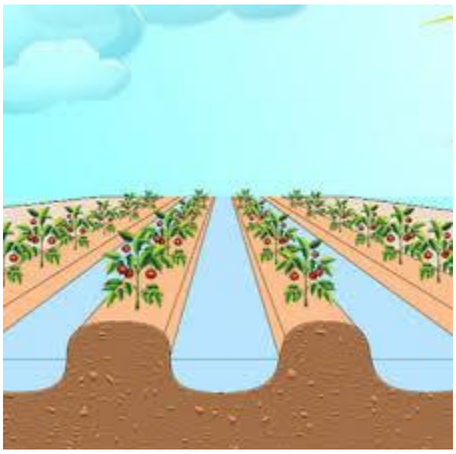


Figure 13 - Surface Irrigation

Surface methods are best suited to deep, medium-textured soils with moderate infiltration rates, on land slopes between 0.1 and 1 percent. Excessive slopes cause uneven advance of water and concentrated erosion in furrows; flat ground produces ponding and uneven infiltration. Land levelling is generally required before installation, which adds substantially to the initial investment and may damage subsoils.

Water-application efficiency of well-managed furrow irrigation in apple orchards ranges from 50 to 70 percent; basin irrigation, where the entire surface is wetted, typically achieves 60 to 75 percent. Both values are well below those achievable with pressurised systems, and surface methods cannot easily deliver the small, frequent applications needed by high-density orchards. Surface irrigation also wets the entire soil surface and the tree trunk, encouraging weed growth and increasing the risk of phytophthora collar rot.

5.2 Sprinkler Irrigation

5.2.1 Overhead Sprinklers

Overhead sprinklers wet the entire orchard, including the tree canopy. They are widely used in temperate-climate apple production for two reasons: integrated frost protection during spring blossom, and cooling of fruit and canopy during summer heatwaves to reduce sunscald. Application efficiency in well-designed installations reaches 60 to 75 percent, but the wetting of foliage increases disease pressure (scab, fire blight) and reduces fungicide persistence.

Figure 14 - Overhead Sprinklers

Capital cost is moderate to high (typically 3,000 to 5,000 USD/ha for permanent installations in Ukraine), and energy demand is the highest of any pressurised system because of the elevated discharge height (typically 6 to 8 m) and required operating pressure (250 to 400 kPa). Overhead systems remain valuable where late spring frosts threaten the variety and the orchard cannot otherwise be protected, but the trend in new Ukrainian commercial plantings is toward drip irrigation supplemented by dedicated frost-protection devices.

5.2.2 Under-tree Sprinklers

Under-tree sprinklers are placed below the canopy on short risers, typically with one sprinkler every 8 to 12 m along the tree row. Each sprinkler wets a circular pattern of 6 to 10 m diameter, covering most or all of the orchard floor. The system avoids canopy wetting and the disease problems of overhead sprinklers and provides moderate application efficiency of 70 to 80 percent. Application rates are lower than overhead systems (2 to 5 mm/h), reducing peak flow demand.

Figure 15 - Under Tree Sprinklers, Nelson

Under-tree sprinklers are well suited to medium-density orchards on relatively level ground with soils of moderate to high infiltration capacity. They are less appropriate for high-density orchards (where the dense canopy intercepts much of the spray) and for windy sites. Modern designs with low-trajectory nozzles can be operated effectively even with light winds and within partially closed canopies. They have lost ground to drip irrigation in new Ukrainian commercial orchards but remain common in mid-density orchards from the 1990s and 2000s.

5.2.3 Microsprinklers

Microsprinklers (sometimes called minisprinklers or microjets) are small spray or spinner emitters operating at 100 to 250 kPa and discharging 20 to 100 L/h each. They are typically installed at one or two per tree, on stake risers of 20 to 40 cm height, and wet a circular or sector pattern of 1.5 to 3 m radius. Modern designs use pressure-compensating nozzles that maintain uniform discharge over a wide pressure range.

Figure 16 - Microsprinklers, Agrimotion

Microsprinklers combine many of the advantages of drip irrigation (precise placement near the trees, low-pressure operation, easy compatibility with fertigation) with a larger wetted volume of soil that better supports root systems on sandy soils. They are particularly well suited to coarse-textured soils where drip irrigation produces a too-small wetted volume, and to young trees where the wetted radius of 1.5 to 3 m matches the developing root zone. Microsprinklers also accept lower-quality water than drip emitters (their larger orifices are more tolerant of suspended solids) and are well suited to surface water sources after coarse filtration.

Limitations include greater evaporative loss than drip (10 to 15 percent of applied water compared with 3 to 5 percent), higher labour for maintenance (clearing nozzles, replacing stakes after cultivation), and the need for slightly higher operating pressures. Microsprinklers are widely used in modern Ukrainian apple orchards on sandy soils in the central and southern regions, and in young orchards before transition to drip.

5.3 Drip Irrigation

Drip irrigation delivers water at low rates (typically 1 to 8 L/h per emitter) through emitters placed on or near the tree row. It has become the dominant system for new commercial apple plantings in Ukraine and globally, and rightly so: water-application efficiency commonly exceeds 90 percent, fertigation is straightforward, foliage and fruit remain dry, and the system is compatible with virtually any soil and topography.

5.3.1 Surface Drip

Surface drip lines are placed on the soil surface or suspended 10 to 30 cm above it along each tree row. Two configurations are common: a single lateral per tree row, sometimes with two emitters per tree, or a double lateral arrangement (one on each side of the trunk) used principally in young high-density plantings. Emitter spacing is typically 0.3 to 0.75 m along the lateral; pressure-compensating emitters are preferred to maintain uniform discharge over the length of the row and on sloping ground.

Figure 17 - Surface Drip Irrigation

Surface drip systems are inexpensive to install (typically 2,500 to 4,000 USD/ha for materials in 2023 Ukrainian conditions), simple to inspect and maintain, and easy to retrofit. The disadvantages are exposure of laterals to mechanical damage (from cultivation, mowing, and wildlife — particularly hares in winter), exposure to UV degradation (rated working lives of modern surface drip lines are 7 to 12 years), and concentration of root systems near the surface, which can increase frost susceptibility.

5.3.2 Subsurface Drip

Subsurface drip irrigation (SDI) places drip laterals 15 to 30 cm below the soil surface. Modern SDI laterals incorporate emitters with anti-siphon membranes that prevent root intrusion and soil ingress. The advantages are reduced evaporation from the soil surface, complete protection from mechanical damage and UV, and the absence of any surface obstruction to cultivation and harvest operations. Some authors report water savings of 10 to 20 percent compared with surface drip in apple, though the evidence under Ukrainian conditions is limited.

Figure 18 - Subfuface Drip, Rivulis

The principal drawbacks of SDI in apple are difficulty of inspection (problems are detected only by their effects on the trees), the need for very careful filtration to prevent emitter clogging that cannot be cleared by surface flushing, and substantially higher installation cost. Specialised tools are required to install laterals at uniform depth, and root intrusion remains a long-term risk in some installations. SDI is increasingly used in new high-value Ukrainian apple plantings where soil cultivation continues throughout the orchard life, and where surface drip would be repeatedly damaged.

5.4 System Selection Criteria

The choice of irrigation system for an orchard should rest on a careful evaluation of the following factors, in approximate order of importance:

- Water source and water quality. Drip systems require well-filtered water (typically below 100 NTU turbidity and free of large suspended solids); microsprinklers can accept lower-quality water; surface systems are tolerant of nearly any quality.
- Capital availability and payback expectations. Drip systems have the highest capital cost (typically 3,500 to 6,000 USD/ha in Ukraine for fully installed systems including pump, filter, and fertigation), but the lowest operating cost per unit of fruit produced.
- Soil texture and depth. Sandy soils favour microsprinklers, which produce a larger wetted volume than drip; clay soils favour drip; shallow soils need frequent low-volume application that drip provides naturally.
- Topography and orchard layout. Steep or irregular sites favour pressure-compensating drip; large uniform blocks may permit surface systems.
- Crop value and management intensity. High-density, high-value plantings of premium varieties justify drip; lower-value orchards may be better served by less expensive systems.
- Energy supply and reliability. Pressurised systems require reliable electrical supply or robust diesel backup; surface systems do not.

- Frost protection requirement. Where late spring frosts are frequent and the variety is sensitive, an overhead sprinkler system may be justified — usually as a complement to a primary drip or microsprinkler installation.
- Available labour and technical skill. Drip and microsprinkler systems require trained operators able to monitor pressures, flush filters, and detect emitter problems; surface systems can be operated with less technical preparation.

5.5 Comparative Advantages and Limitations

Table 4 summarizes the principal characteristics of the systems described in this chapter, as a quick reference for selection decisions. The values are typical of Ukrainian commercial conditions and assume competent design and operation; poorly managed systems of any type will perform substantially below the values shown.

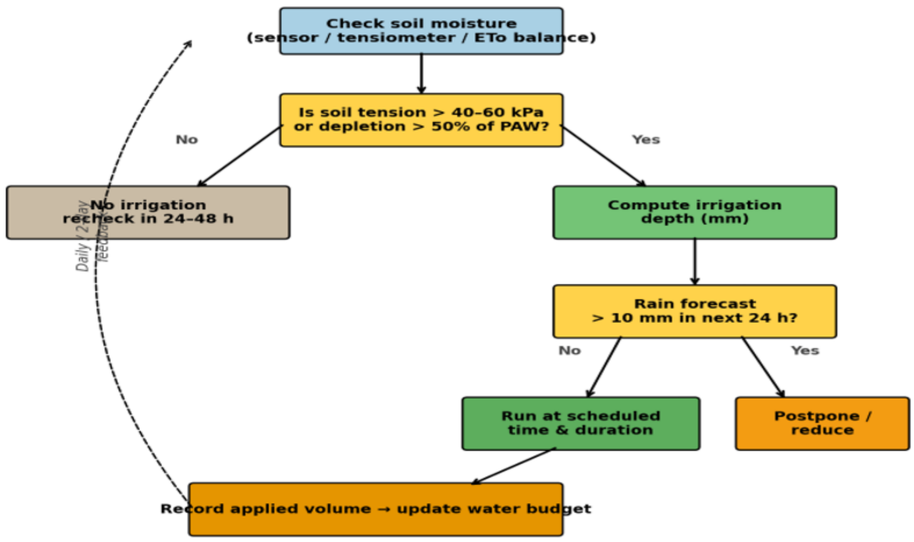
System	Efficiency (%)	Capital (USD/ha)	Energy	Fertigation	Frost protection
Furrow	50–70	500–1,500	None	Difficult	No
Basin	60–75	700–1,800	Low	Difficult	No
Overhead sprinkler	60–75	3,000–5,000	High	Possible	Excellent
Under-tree sprinkler	70–80	2,500–4,000	Medium	Good	Limited
Microsprinkler	80–88	2,800–4,500	Medium	Excellent	Limited
Surface drip	88–95	3,500–5,500	Low–Medium	Excellent	No
Subsurface drip	90–95	4,500–7,000	Low–Medium	Excellent	No

Table 4 — Comparative characteristics of irrigation systems for Ukrainian apple orchards. Efficiency is application efficiency (water reaching the root zone / water leaving the source); capital costs are for typical installations in 2023.

6 Irrigation Scheduling

Scheduling is the process of deciding when to irrigate and how much water to apply. It is the single most important determinant of irrigation performance — far more important than the choice of hardware. Even the most expensive drip system delivers poor results if it is operated by guesswork; conversely, a modest microsprinkler installation operated to a well-designed schedule will produce excellent fruit yields and quality.

Modern scheduling practice combines three broad approaches: monitoring soil moisture directly, measuring plant water status, and calculating water demand from weather data. The most reliable schedules use at least two of the three, with the others serving as cross-checks. This chapter describes each method in turn and concludes with the integrated decision process used in practice.



Decision flow for irrigation scheduling combining soil moisture, weather, and plant indicators. The schedule converges on the same answer whether started from any of the three monitoring approaches; their combination reduces uncertainty.

6.1 Soil Moisture Monitoring Methods

Direct measurement of soil moisture is the most intuitive approach to scheduling and forms the basis of most operational systems. Three families of methods are in routine commercial use: tension-based methods (tensiometers and matric-potential sensors), water-content methods (capacitance, time-domain reflectometry, and neutron probe), and the laboratory standard, gravimetric sampling. Each measures a different physical property and has its appropriate role.

Figure 19 - Soil moister manuel methode

6.1.1 Tensiometers

A tensiometer is a sealed water-filled tube with a porous ceramic tip at the bottom and a vacuum gauge or pressure transducer at the top. As the surrounding soil dries, water is drawn out of the tube through the ceramic tip, creating a partial vacuum that registers on the gauge. The reading expresses the soil matric potential — the force with which water is held in the soil — directly in centibars (cb) or kilopascals (kPa).

Irrometers indicate the level of soil dryness by measuring the soil water tension (suction pressure).

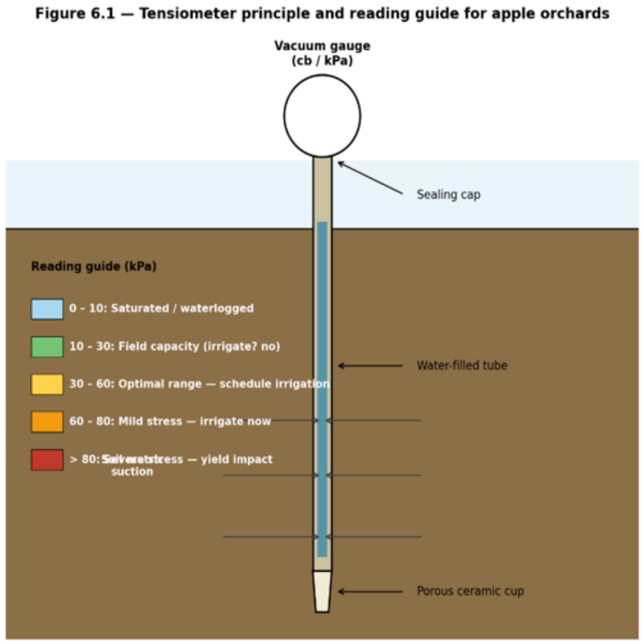


Figure 20 - Tensiometer cross-section and reading guide. The instrument measures soil matric potential directly, expressed in centibars (cb): readings of 0–10 cb indicate saturated soil, 30–50 cb indicate the typical irrigation trigger range for apple, and readings above 80 cb may indicate that the instrument has lost vacuum.

Tensiometers are well suited to apple orchards on medium to fine-textured soils. They are inexpensive (typically 30 to 80 USD each), simple to install, and easy to read by inspection. Their principal limitation is a working range of 0 to about 80 cb; in sandy soils that dry rapidly past this point, tensiometers fail to track further drying. For most apple irrigation purposes — where the goal is to maintain matric potential between 15 and 60 cb — this limitation is unimportant.

Standard practice in commercial Ukrainian orchards is to install pairs of tensiometers at 30 cm and 60 cm depth at 4 to 8 representative locations per orchard block. Irrigation is triggered when the shallow tensiometer (which dries first) reaches a target value — typically 30 cb on sandy loam, 40 cb on loam, and 50 cb on clay loam. The deep tensiometer is used to check that irrigation events have been long enough to refill the entire root zone, and to detect over-irrigation (deep tensiometer permanently near 0 cb).

Figure 21 - Irrometer indicate the level of soil dryness by measuring the soil water tension (suction pressure)

6.1.2 Capacitance and TDR Sensors

Capacitance sensors (also called frequency-domain reflectometry, FDR) and time-domain reflectometry (TDR) probes measure the dielectric constant of the soil, which is strongly correlated with volumetric water content. They report water content as a percentage by volume and can produce continuous logged data at intervals of 15 minutes or less. Modern probes integrate readings over multiple depths (typically 10, 20, 30, 50, 70, and 100 cm) on a single shaft.

Figure 22 - Capacitance and TDR Sensors

Capacitance and TDR systems provide much richer information than tensiometers: the continuous data clearly show the diurnal pattern of root water uptake, the depth of wetting after irrigation events, and the gradual depletion between events. Modern systems include data telemetry by GSM or LoRaWAN, with real-time web dashboards accessible from a smartphone. Such installations are now standard in larger Ukrainian commercial orchards.

The principal limitations are higher capital cost (typical multi-depth telemetric probes cost 800 to 1,500 USD per installation), the need for soil-specific calibration (factory calibrations may differ from field readings by 5 to 15 percent volumetric water content on stony or organic soils), and dependence on a reliable power supply and data network. For most apple orchards, two to four telemetric probes per block — one in each representative soil type and position — provide adequate spatial coverage.

6.1.3 Gravimetric Sampling

Gravimetric sampling is the laboratory-standard reference method for soil water content. A soil core of known volume is taken, weighed wet, dried at 105 °C for at least 24 hours, and weighed again. The water content is calculated from the mass difference and the volume of the core. Although too slow for operational scheduling, gravimetric sampling is invaluable for calibrating other sensors, for diagnosing problems (such as discrepancies between sensor readings and observed tree behaviour), and for site characterisation before installing a sensor network. Every commercial orchard sensor system should be calibrated against gravimetric samples taken at the time of installation.

6.2 Plant-Based Indicators

Plant-based methods measure the tree itself, which has the advantage of integrating the response to all environmental factors — soil moisture, atmospheric demand, and any limitations on root water uptake from poor aeration, salinity, or disease. They are the most direct measure of plant water status but are more demanding to interpret than soil or weather data.

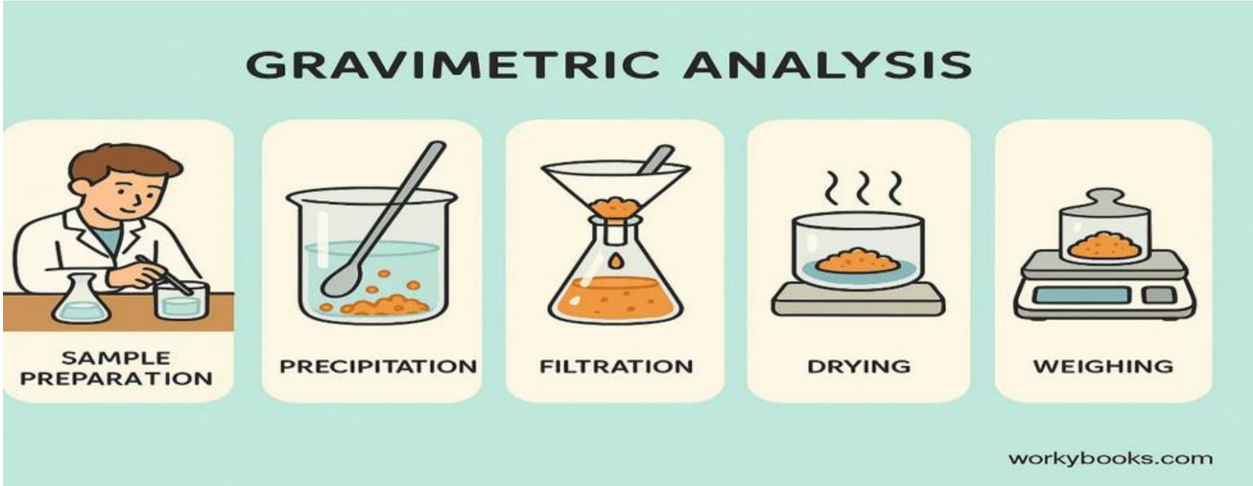


Figure 23 - Gravimetric analysis, workybooks.com

6.2.1 Stem Water Potential

Stem water potential (Ψstem), measured with a pressure chamber on bagged leaves, is the most widely accepted plant-based indicator for apple. A shaded leaf adjacent to the trunk is enclosed in a foil bag for at least one hour to equilibrate with the trunk water potential, then excised and placed in the pressure chamber. The pressure required to force water back to the cut surface, in MPa, is the stem water potential. Less-negative values indicate better-hydrated trees; more-negative values indicate stress.

Figure 24 - Stem Water Potential with bagged leaves, PMS Instrument Company

Reference values for mature apple in central and southern Ukrainian conditions are approximately −0.6 to −0.9 MPa for well-irrigated trees, −0.9 to −1.2 MPa for mild stress (suitable for the regulated deficit phases described below), and −1.4 MPa or more negative for severe stress that depresses fruit growth and yield. Measurements are made at midday (12:00 to 14:00 solar time) in clear weather on at least 4 to 6 trees per block; means are interpreted against the reference values.

Pressure chambers cost 1,500 to 3,500 USD and require trained operators, which has limited their adoption to research-oriented and very large commercial enterprises. They are particularly useful as a definitive cross-check during the implementation of regulated deficit strategies, and for diagnosing under-performing orchards where soil moisture appears adequate but trees show stress.

6.2.2 Leaf Temperature and Stomatal Conductance

Infrared thermometry of canopy temperature provides a rapid, non-contact measure of stress. Stressed leaves close their stomata, reducing transpirational cooling and rising above air temperature. The difference between canopy and air temperature (Tc − Ta) is the simplest stress index; the crop water stress index (CWSI) normalises this difference to a 0–1 scale using upper and lower reference lines. Apple is moderately conservative in stomatal regulation; clear stress signals require Tc − Ta of more than 3 °C in normal conditions.

Hand-held infrared thermometers make spot readings practical for in-field diagnostics. More sophisticated installations use fixed infrared sensors over each block or — increasingly — thermal imagery from unmanned aerial vehicles (UAVs), which can map canopy temperature and identify stressed zones at the resolution of individual trees. Such technologies are entering routine use in advanced Ukrainian orchards.

Figure 25 - Electronic Thermonetor

Direct measurement of stomatal conductance with a leaf porometer provides a more sensitive measure of stress than canopy temperature but is too slow for routine commercial use. It remains an important research tool and is occasionally used in diagnostic trials.

6.3 Weather-Based (ET) Scheduling

Weather-based scheduling uses the equation introduced in Chapter 4: ETc = Kc × ETo, Net irrigation requirement = ETc − Effective rainfall, to predict the daily orchard water demand and accumulate a running soil-water balance. Operationally, the procedure is:

- Each morning, obtain the previous day’s ETo from an automatic weather station or regional service.
- Multiply by the current Kc value (from a calibrated curve such as those in Table 4.2) to obtain ETc.
- Subtract effective rainfall measured at the orchard.
- Add the result to a running deficit counter representing the current depletion of soil water.
- When the deficit reaches a pre-set trigger (typically 30 to 50 percent of available water in the root zone), schedule irrigation to refill the soil to field capacity, or to a target depletion below field capacity if a deficit-irrigation strategy is in use.

Weather-based scheduling has the advantage of being predictive rather than reactive: the system "knows" the demand before the trees show any sign of stress, and irrigation can be scheduled to fit operational constraints (working hours, power tariff structures, harvest activities). Its principal weakness is the cumulative drift of the soil-water balance if Kc values, ETo, or effective rainfall are systematically over- or underestimated. Standard practice is to reset the calculated balance against periodic direct measurements of soil moisture, typically every 7 to 14 days during the peak season.

6.4 Decision Support Tools and Models

Numerous software tools and models have been developed to assist with apple irrigation scheduling. They differ in complexity, cost, and degree of integration with sensor and weather networks. Categories include:

- Simple spreadsheet-based water-balance calculators that combine ETo from a weather service with Kc tables and effective rainfall. These are free, transparent, and suitable for any farm with basic computing literacy.
- Commercial farm-management platforms with integrated dashboards showing real-time soil moisture, weather forecasts, and recommended irrigation schedules. Examples include several systems available in Ukraine that combine telemetric soil probes with FAO-56 water-balance modelling.
- Research-grade physical models such as APPLES, RZWQM2, or HYDRUS that simulate soil water flow and crop physiology in detail. These require extensive site characterisation and are used principally in research and policy contexts.
- Operational forecasting services that combine ETo forecasts (typically 7–10 days ahead) with weather forecasts to project irrigation demand, allowing pre-emptive scheduling around forecast rainfall.

For most commercial Ukrainian orchards, a combination of a simple water-balance spreadsheet, soil sensors with telemetry, and a regional weather service provides adequate scheduling capability at modest cost. The single most important investment is in the time of a trained scheduler who synthesises the data into operational decisions; software cannot replace this judgement.

6.5 Regulated Deficit Irrigation (RDI) Strategies

Regulated deficit irrigation (RDI) is a strategy that deliberately applies less water than ETc during specific phases of the season, with the objective of saving water, improving fruit quality, and controlling vegetative growth. It exploits the physiological observation that mild water stress during the late cell-division phase (approximately 60 to 100 days after full bloom) reduces shoot growth more than fruit growth in apple,

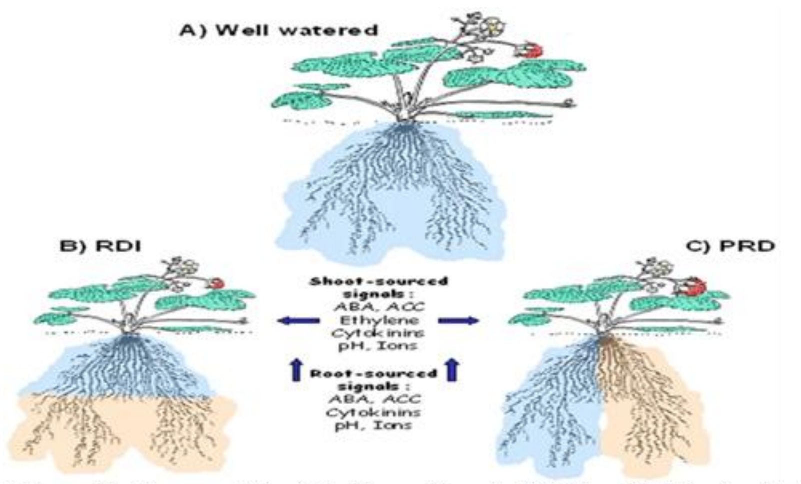


Figure 26 - Schematic diagram of the irrigatoin pattern in Fl, RDI and PRD by Davis and Harfung 2004

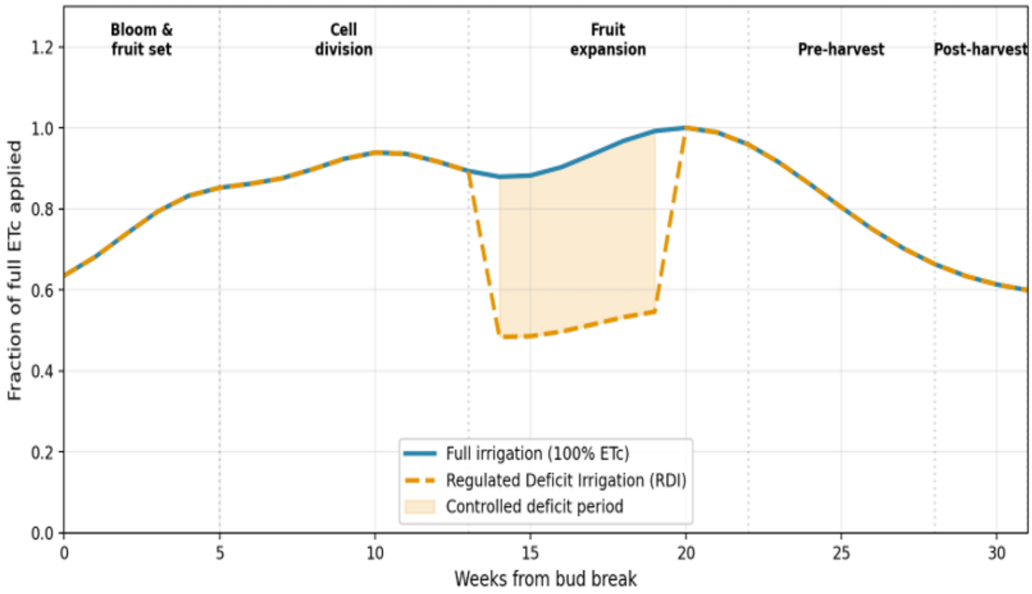


Figure 27 - Regulated deficit irrigation strategy versus full irrigation. Mild water stress (Ψstem of −1.0 to −1.2 MPa) is imposed during the cell-division to mid-expansion period (shaded), with full irrigation restored before final fruit expansion to preserve fruit size.

producing more compact trees with similar fruit yields and improved colour and dry-matter content.

A typical RDI schedule for apple in Ukrainian conditions consists of full irrigation (replacing 100 percent of ETc) from bud break to about 30 days after full bloom; a deficit period (60 to 75 percent of ETc) from about 30 to 90 days after full bloom, with stem water potential allowed to fall to −1.0 to −1.2 MPa; and full irrigation again from 90 days after full bloom until harvest. Post-harvest irrigation is held at a moderate level (50 to 70 percent of ETc) to allow leaf senescence and cold hardening.

Successful RDI requires close monitoring: it is not safe to apply blindly. Recommended monitoring practice is daily soil moisture and weekly stem water potential during the deficit period, with rapid return to full irrigation if any indicator suggests excessive stress. Reported water savings of 15 to 30 percent compared with full irrigation are achievable in central and southern Ukraine without yield loss, with frequent improvements in fruit colour and storage life.

7 Water Requirements by Orchard Stage

Apple orchards pass through distinct stages from planting to maturity, and their water requirements change correspondingly. The needs of a newly planted tree, a 4-year-old leader trained on a trellis, and a 15-year-old mature tree on M9 rootstock are profoundly different. This chapter provides indicative water requirements for each stage and discusses the implications for irrigation system sizing and scheduling.

7.1 Newly Planted Trees

The first growing season after planting is critical for orchard establishment. Newly planted trees have small, damaged root systems confined to the original nursery soil ball; they cannot extract water from any significant volume of soil and are entirely dependent on irrigation water applied within the immediate vicinity of the trunk. Failure to maintain adequate moisture in the first 30 cm around the trunk during the first 60 to 90 days after planting is the most common cause of poor establishment.

Typical water requirements for newly planted trees in Ukrainian conditions are modest in absolute terms — 2 to 6 litres per tree per day, depending on weather — but must be delivered to a very small soil volume. Microirrigation (drip or microsprinkler) is strongly preferred for this purpose. Furrow or sprinkler systems designed for mature orchards over-apply water broadly without delivering enough close to the trunk and produce both poor establishment and high disease pressure.

Practical recommendations for first-season irrigation:

- Drip-irrigated orchards: install one 2 to 4 L/h emitter within 15 to 30 cm of each trunk, in addition to the permanent emitters that will serve the mature tree. Run irrigation daily during the establishment period.
- Microsprinkler-irrigated orchards: ensure the wetted pattern includes the trunk position. In some installations the permanent microsprinkler is supplemented by a temporary drip emitter directly at the trunk.
- Maintain soil moisture in the top 30 cm continuously close to field capacity. Tensiometer readings should not exceed 20 cb in this depth during the establishment period.
- Continue intensive trunk-zone irrigation until vigorous new growth confirms successful establishment, typically 60 to 90 days after planting.

7.2 Young, Non-Bearing Orchards

From the second growing season until the orchard reaches commercial bearing — typically years 2 to 4 on dwarfing rootstocks, longer on semi-dwarf and standard rootstocks — water requirements increase rapidly as canopy and root systems expand. Indicative seasonal water requirements are 200 to 350 mm/year in year 2, 300 to 450 mm in year 3, and 450 to 600 mm in year 4 of growth, depending on region.

The objective during this period is rapid, healthy vegetative growth to fill the assigned space and establish the desired tree structure. Mild water stress that would be tolerable in a bearing orchard is not appropriate at this stage; it reduces canopy development, delays the start of bearing, and reduces lifetime productivity. RDI strategies are inappropriate for non-bearing orchards.

Practical recommendations for non-bearing orchards include irrigation by drip or microsprinkler with regular schedule reviews as the trees grow; matching irrigation duration to a developing root system that increases in depth from 30 cm in year 1 to 60 to 80 cm by year 4; and inclusion of regular fertigation during the growing season to support vigorous growth.

7.3 Mature, Bearing Orchards

Mature, bearing orchards have stable water requirements that depend principally on tree density, rootstock, canopy training, climate, and management of the orchard floor. Table 7.1 presents indicative total seasonal water requirements and peak daily requirements for mature commercial apple orchards in the principal Ukrainian production regions.

Region	Seasonal ETc (mm)	Effective rain (mm)	Net irrig. (mm)	Peak daily (mm/day)
Vinnytsia (forest-steppe)	550	320	230	5.5
Kyiv (forest-steppe)	580	300	280	5.8
Kherson (steppe)	740	180	560	7.5
Mykolaiv (steppe)	710	200	510	7.2
Zakarpattia (sub-Carpathian)	520	420	100	5.2
Lviv (western)	500	400	100	5.0

Table 5 — Indicative seasonal water requirements for mature, bearing apple orchards in principal Ukrainian regions. Seasonal ETc assumes Kc curves from Table 4.2 and full canopy cover; net irrigation is ETc minus effective rainfall (75 percent of average rainfall (75 percent of average rainfall)

The values in Table 5 are starting points for design calculations; site-specific values should be developed for each orchard using the actual long-term weather record and locally calibrated Kc values. The peak daily requirement is the critical value for system capacity design: the irrigation system must be able to deliver this rate continuously, with allowance for downtime and maintenance.

7.4 High-Density vs. Traditional Orchards

Modern apple production has progressively shifted toward high-density plantings of 1,500 to 4,000 trees per hectare on dwarfing rootstocks (predominantly M9 in Ukraine, with some M26 and B9), trained on trellised slender spindle or similar central-leader systems. These have substantially different water management characteristics than traditional plantings of 200 to 600 trees per hectare on semi-dwarf or standard rootstocks.

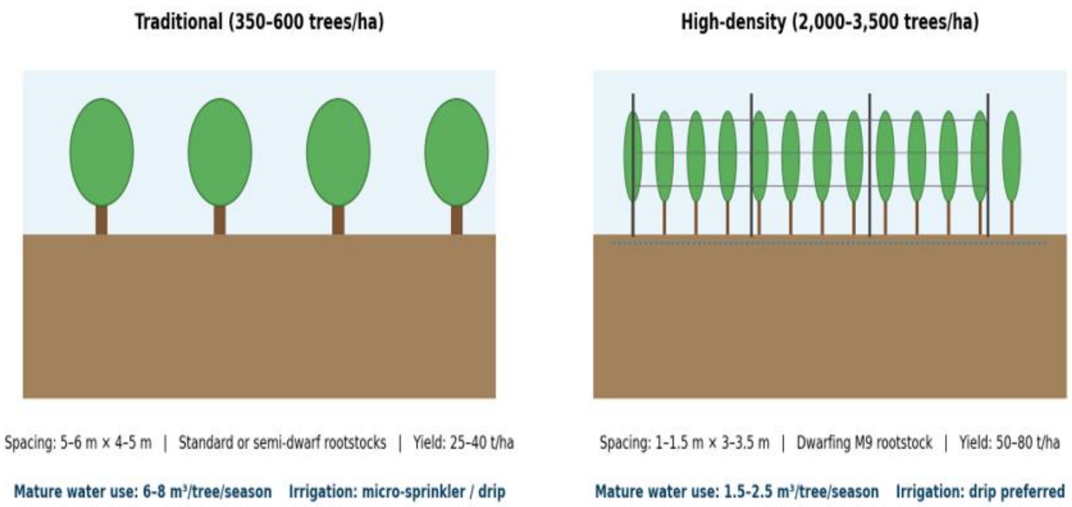


Figure 28 - Schematic comparison of traditional (left, ~400 trees/ha on semi-dwarf rootstock) and high-density (right, ~3,000 trees/ha on M9) apple orchard systems. The high-density orchard has a much earlier increase in canopy cover, higher peak Kc, and greater susceptibility to short-term water stress because of shallow root systems.

Key differences in irrigation behavior between high-density and traditional systems include:

- Earlier canopy closure and faster increase in Kc: high-density orchards reach near-mature ETc in years 3 to 4; traditional orchards take 7 to 10 years.
- Shallower root systems on dwarfing rootstocks: 60 to 80 percent of roots in the top 50 cm of soil, compared with 30 to 50 cm depth distribution that extends to 1.0 to 1.5 m for semi-dwarf systems.
- Higher sensitivity to short-term water stress due to limited soil-water buffer in shallow root zones. High-density orchards may require irrigation every 1 to 3 days at peak season; traditional orchards can often go 7 to 10 days between irrigations.
- Greater suitability for drip and microsprinkler systems with frequent, low-volume applications; lower suitability for surface irrigation.
- Higher peak Kc values (up to 1.15 for well-managed high-density orchards) due to denser canopy and complete row closure.

For the design of irrigation systems on high-density orchards, the small soil-water buffer is the critical consideration. The system must be sized to refill the small effective root volume on the peak day of demand, and capable of operating with short intervals between irrigations. A design that would be conservative for a traditional orchard may be inadequate for a high-density planting on the same site.

8 Fertigation

The injection of fertilizers (fertigation) and crop-protection chemicals (chemigation) through the irrigation system transforms what would otherwise be merely a water-delivery system into the principal vehicle for nutrient management of the orchard. Properly executed, fertigation increases nutrient-use efficiency by 30 to 50 percent compared with broadcast or banded soil applications, reduces labour, and improves response time to nutritional problems. It is now standard practice in all new commercial apple orchards in Ukraine equipped with pressurised irrigation.

8.1 Principles of Fertigation

The principle of fertigation is simple: water-soluble fertilisers are dissolved into the irrigation stream at a controlled rate and delivered directly to the root zone with each irrigation event. The amounts and timing of nutrient applications can be tailored precisely to crop demand, since both can be varied from one irrigation to the next. Compared with conventional soil applications, fertigation offers several distinct advantages:

- Nutrients are placed exactly where roots are most active — within the wetted zone of the emitter or microsprinkler — reducing losses to leaching, fixation in non-rooting volumes, and uptake by weeds.
- Frequent small applications (often called "spoon-feeding") match the temporal pattern of crop demand and reduce the risk of leaching losses, particularly of nitrogen on light soils and following heavy rainfall.
- Application is by the same equipment used for irrigation, with no separate field operations needed; this is particularly important for fully-canopied high-density orchards where ground-based applications become difficult.
- Response to in-season diagnostic information (visual symptoms, leaf analysis) is rapid; corrective applications can be made within hours rather than days.
- Fertilisers in solution have higher availability than granular forms applied to dry soil surfaces.

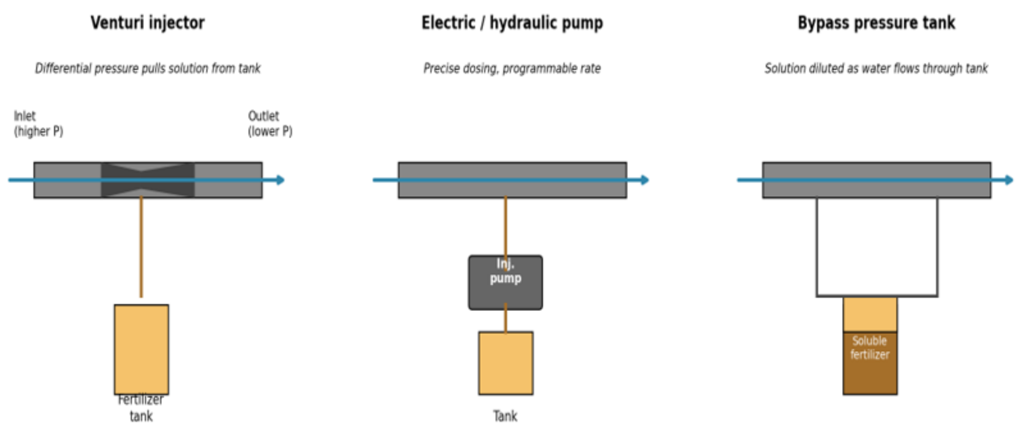


Figure 29 - Three principal injection methods used in apple fertigation (a) Venturi injector — simple, no moving parts, but pressure loss; (b) piston or diaphragm injection pump — precise, adjustable; (c) bypass tank — inexpensive but limited control over injection profile.

Limitations of fertigation include the requirement for water-soluble fertilisers (more expensive per unit of nutrient than agricultural grades), the need for compatibility testing among fertilisers and with the irrigation water (precipitates can clog emitters), and the requirement for operator training in nutrient management, chemistry, and equipment.

8.2 Nutrient Injection Equipment

Three main classes of injection equipment are in routine commercial use, each with distinct characteristics:

Figure 30 - Injection unit, by VGB

Venturi injectors operate on the venturi principle: a constriction in the main pipe creates a pressure drop that draws concentrated fertiliser solution from an open tank through a flexible suction tube. They are simple, robust, have no moving parts, and are inexpensive (typical commercial units cost 100 to 400 USD). The principal limitation is a pressure loss of 20 to 30 percent across the injector, which must be allowed for in system design. Injection rates can be adjusted but are not easily metered precisely.

Injection pumps (piston, diaphragm, or peristaltic) provide accurate, adjustable injection independent of main-line pressure. They are typically driven by an electric motor or — particularly in larger commercial systems — by hydraulic flow itself (water-driven proportional injection). Capital cost is higher (typical 600 to 2,500 USD) but injection rates can be precisely set, modulated, or programmed throughout an irrigation event. They are the standard choice for commercial Ukrainian orchards larger than about 5 hectares.

Bypass tanks (pressure differential tanks) are sealed tanks containing dry or concentrated liquid fertiliser; a small flow is diverted from the main pipe through the tank, dissolving fertiliser progressively. They are inexpensive but produce a declining concentration profile during the irrigation event and are unsuitable where precise fertigation is required. Their use in modern Ukrainian commercial orchards is limited to small operations and emergency back-up.

Regardless of injection method, several auxiliary components are required for safe operation: a check valve between the injection point and the water source to prevent backflow contamination of the source; a vacuum breaker upstream of the injector to ensure that any backflow contains air, not fertiliser solution; isolation valves; and downstream filtration sufficient to remove any precipitates or undissolved particles before they reach the emitters.

8.3 Scheduling Nutrients with Irrigation

A typical annual fertigation programme for a mature, bearing apple orchard in Ukrainian conditions delivers approximately 60 to 120 kg N/ha, 20 to 40 kg P2O5/ha, 80 to 180 kg K2O/ha, and 30 to 60 kg Ca/ha, with calcium chloride applications timed to the final fruit-expansion period to support fruit firmness. Magnesium, sulphur, and micronutrients (B, Zn, Fe, Mn) are added as indicated by leaf and soil analysis.

The temporal pattern of application follows the seasonal demand of the orchard:

- Bud break to bloom (late April–mid May): low to moderate N (10–20 percent of seasonal total), modest K, minimal Ca and P.
- Fruit set to early cell division (mid May–mid June): peak N application (25–30 percent of total), supporting both fruit and shoot growth.
- Cell division to mid-expansion (mid June–early August): high N continues (25–30 percent), increasing K (40–50 percent of seasonal K total), beginning Ca applications.
- Final expansion to harvest (August–early September): tapering N, sustained K, intensive Ca applications particularly on varieties susceptible to bitter pit (Bramley, Cox, Honeycrisp, some Gala strains).
- Post-harvest (September–leaf fall): modest N (5–10 percent of total) to support bud development and reserve accumulation, no further Ca or K.

Standard practice is to fertigate at most or every irrigation event during the active growing season, with each event delivering a small fraction of the seasonal total. Concentrations in the irrigation stream should not exceed approximately 1.5 g/L of total dissolved fertiliser to avoid osmotic stress at the emitter and emitter clogging from precipitation. Each fertigation event should conclude with a clear-water flushing period of at least 15 minutes to clear all fertiliser from the laterals and emitters before the system is shut down.

8.4 Increase in Oxygen Content of Water

Dissolved oxygen, usually written as DO and measured in milligrams per litre, is simply the amount of free oxygen gas physically held in the water. It is not the oxygen that is locked inside the H2O molecule itself, but extra O2 that has come out of the air or out of an aeration system and stays in solution. For irrigation, DO is one of the most underrated water quality parameters, because plants do not only breathe through their leaves, they also breathe through their roots.

Roots need oxygen to respire. Respiration is what gives the root cells the energy to actively pump nutrients out of the water and into the plant. When DO drops, nutrient uptake slows down even if the fertiliser levels in the water are perfect. Growers often see this as deficiency symptoms in a crop that is, on paper, fed correctly. The real problem is not the nutrients, it is the oxygen.

DO in irrigation water also decides which microbes dominate around the roots. In oxygen-rich water, aerobic and mostly beneficial bacteria thrive and they help break down organic matter, suppress disease, and keep the rhizosphere healthy.

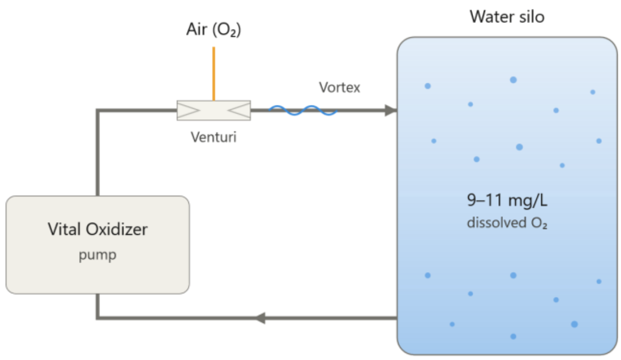


Figure 31 - Schematic Vital Oxidizor

8.5 Chemigation

Chemigation — the application of pesticides, fungicides, or other crop protection chemicals through the irrigation system — has more limited application in apple than fertigation. The most common chemigation applications are:

- Acidification of irrigation water using sulphuric, nitric, or phosphoric acid to maintain pH below 6.5 and prevent precipitation of calcium and bicarbonates in the irrigation system. This is more accurately described as water treatment than chemigation.
- Injection of chlorine (as sodium hypochlorite) for periodic shock treatment to control biofilm and bacterial slime in laterals.
- Application of soil-active insecticides and nematicides to the root zone; this has largely been abandoned in modern Ukrainian apple production for environmental and resistance-management reasons.
- Injection of soluble plant biostimulants, humic acids, and microbial inoculants — an expanding but as yet not standardised category.

Chemigation requires substantially stricter safety controls than fertigation. Where pesticides are involved, regulatory requirements typically include: double back-flow prevention to protect the water source; an interlock that stops chemical injection automatically if irrigation flow fails; chemical-resistant injection equipment; and full record-keeping of applications. Direct foliar applications of fungicides through overhead sprinklers, once practised in some Ukrainian orchards, are no longer recommended for fire-blight-susceptible cultivars because of the disease-spreading effects of wetting the canopy.

9 System Design and Installation

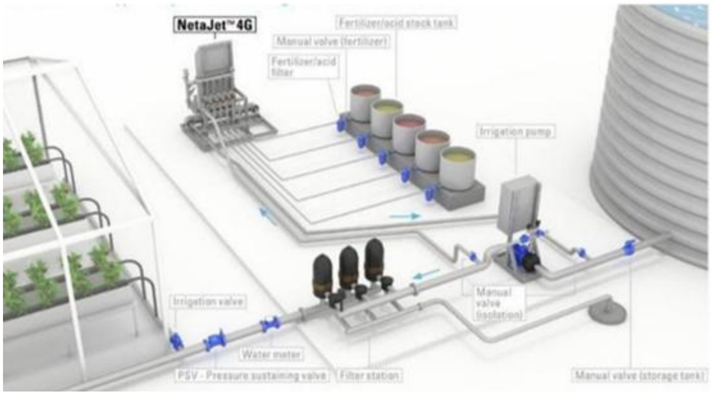


Figure 32 - Irrigation Design

System design translates the agronomic requirements developed in earlier chapters — peak daily water demand, soil characteristics, orchard layout — into a specific hydraulic design: pump capacity, pipe sizes, filter selection, emitter type and spacing, and the operational sequencing of valves and zones. Good design must satisfy hydraulic, agronomic, and economic constraints simultaneously, and must allow for future maintenance and expansion.

This chapter outlines the principal design steps and presents the rules of thumb used in routine commercial design in Ukrainian conditions. For large or complex installations, specialised design software and an experienced irrigation engineer are recommended; what follows is suitable for understanding such designs, for sketching small to medium installations, and for evaluating proposals from suppliers.

9.1 Hydraulic Design Principles

The hydraulic design begins with the peak daily water requirement (mm/day) and works through a sequence of conversions to specify pipe sizes, pressures, and flow rates at each point in the system. The standard steps are:

- Compute the peak gross irrigation requirement: peak ETc divided by the assumed application efficiency (e.g., 0.92 for surface drip). Add a 10–20 percent safety margin for unfavourable years and system downtime.
- Compute the system flow rate from the gross requirement and the desired operating time per day. Standard practice is to design for 16 to 20 hours per day operation at peak; a higher figure provides little margin for breakdowns and maintenance.
- Divide the orchard into hydraulic zones, each operated as a unit, such that the total flow at any time matches the system flow rate. The number of zones depends on block size, topography, and crop variety; smaller and more numerous zones offer greater operational flexibility at higher cost.
- Size the main pipe, sub-mains, and laterals based on the flow they must carry, with pressure losses kept within design limits. Typical loss budgets are 10 percent of operating pressure across the main, 5 percent across the sub-main, and 10 percent along the lateral — corresponding to overall uniformity (Christiansen uniformity coefficient) of about 90 percent.
- Select emitters by required discharge rate and spacing. The wetted volume must cover the active root zone; on sandy soils this means closer emitter spacing or use of microsprinklers.

- Specify the pump and motor: total dynamic head equals the static lift plus pipe losses plus required emitter operating pressure (typically 100 to 150 kPa for drip and 100 to 250 kPa for microsprinklers); pump capacity equals the system flow rate.
- Specify filtration: type and capacity based on water quality and emitter sensitivity.

A worked design example for a 10 ha block in central Ukraine with peak ETc of 6 mm/day, drip system at 92 percent efficiency, operating 18 hours per day, demonstrates how these steps interact. The gross daily requirement is 6 / 0.92 × 1.15 = 7.5 mm, which equals 750 m^3/day for 10 ha; spread over 18 hours, this is approximately 11.6 L/s or 42 m^3/h. With 4 hydraulic zones operated sequentially, each zone of 2.5 ha must deliver the same 42 m^3/h. At a typical drip lateral discharge of 1.5 L/h per emitter at 0.5 m spacing, this translates to specific pipe sizes that the designer then verifies against pressure-loss limits.

9.2 Pump and Filtration Requirements

The pump and filtration train is the heart of the irrigation system. Pump selection is determined by the system flow rate, total dynamic head (TDH), the available power supply, and the variability of demand among different operating zones. For most commercial Ukrainian apple orchards, electric centrifugal pumps directly coupled to three-phase motors are standard, with submersible pumps where the water source is a deep well and surface pumps for shallow wells, ponds, or rivers.

Figure 33 - Mobile pump system

Pump capacity should match the largest single zone flow rate plus an allowance of 5 to 10 percent for filter pressure rise and gradual wear. Variable-frequency drives (VFDs) on the pump motor are increasingly common in new Ukrainian installations: they allow the pump speed to be matched to the actual zone flow, reducing energy consumption by 20 to 40 percent compared with throttled fixed-speed operation and providing soft-start that reduces hydraulic shock and extends equipment life.

Figure 34 - Water Filter Unit

Filtration is critical for drip and microsprinkler systems and is the most common cause of avoidable irrigation failures. Filter selection depends on water source and emitter sensitivity:

- Surface water (ponds, rivers, canals): typically requires sand-media filtration as primary stage (capacity 50 to 100 µm), followed by screen or disc filtration for fine polishing (80 to 130 mesh, equivalent to 110 to 180 µm).

- Groundwater from wells: usually requires only screen or disc filtration (130 to 200 mesh) for typical drip emitters, unless iron, manganese, or biological activity is significant.
- Drip emitters with very small orifices (under 1 L/h): require finer filtration (200 mesh or finer); larger emitters and microsprinklers tolerate coarser filtration.

Sand filters are sized by water flow rate and water quality; typical capacity is 30 to 50 m³/h per filter tank, with multiple tanks operated in parallel for larger systems. They require backflushing — automatic in modern installations — when the pressure drop across the filter exceeds about 0.5 bar. Disc and screen filters are also backflushable and have lower energy consumption than sand filters; they are appropriate where biological load is low.

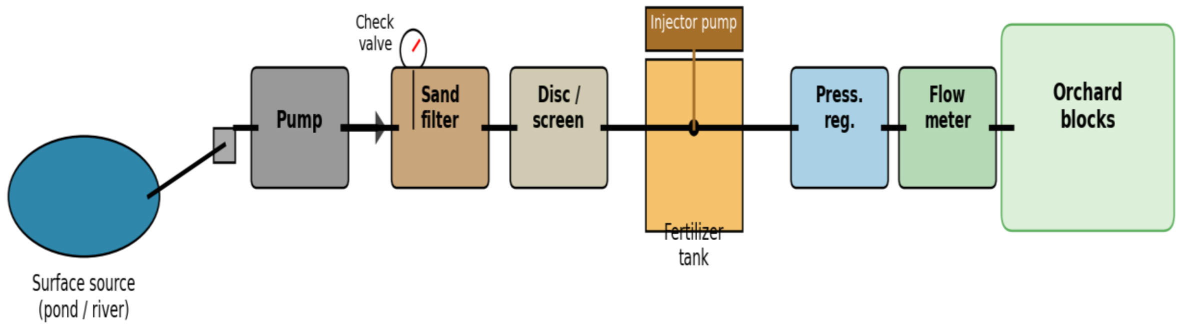


Figure 35 - Schematic of a typical pump and filtration train for an apple orchard drip system (1) intake screen, (2) primary pump, (3) sand or hydrocyclone filter for bulk solids, (4) injection point for fertigation, (5) secondary screen or disc filter for fine filtration, (6) pressure regulator, (7) flow meter, (8) main shut-off valve to field.

9.3 Pipe Layout and Emitter Spacing

The pipe layout of a typical Ukrainian commercial drip-irrigated apple orchard consists of:

- A main line from the pumphouse to the orchard, sized for full system flow and built of pressure-rated PE or PVC (typically 90 to 160 mm diameter, depending on flow).
- Sub-mains running perpendicular to tree rows, each serving one hydraulic zone (typically 63 to 110 mm).
- Lateral lines running along each tree row, with integrated or attached emitters (typically 16 to 20 mm).
- Optional flushing lines at the far end of each row, connecting all laterals in a zone to a common flush valve.

Emitter spacing depends on soil type and orchard density. For high-density orchards on medium soils, a single lateral per tree row with emitters at 0.4 to 0.5 m spacing — typically 2 m) can be used. For traditional lower-density orchards, two laterals per row (one on each side of the trunk) or multiple emitters concentrated near each tree may be more appropriate.to 4 emitters per tree at 1.2 to 2.0 m tree spacing — is standard. On sandy soils, closer spacing (0.3 to 0.4 m) is needed to overlap wetting patterns. On heavy soils, wider spacing (0.6 to 0.75

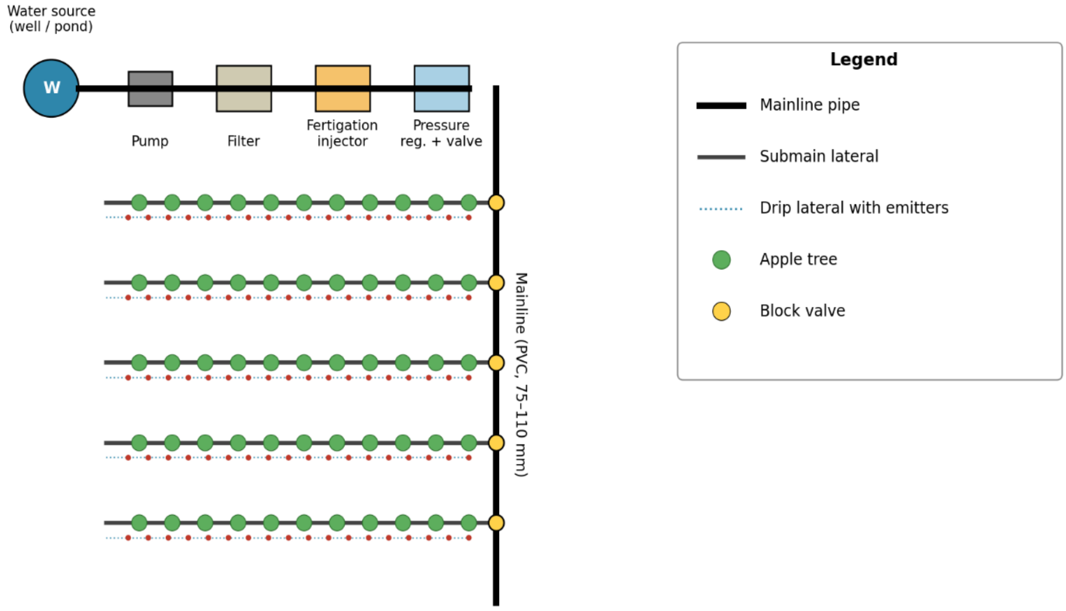


Figure 36 - Plan view of a typical drip irrigation layout for an apple orchard main line (heavy black), sub-mains servicing each block (medium), laterals along each tree row (thin), with emitters spaced along the laterals. Hydraulic zones are demarcated by zone valves; each zone is operated as an independent unit on a programmed schedule.

Pressure-compensating emitters are strongly recommended for all but the smallest, flattest installations. They maintain uniform discharge across a wide pressure range (typically 80 to 350 kPa), automatically compensating for elevation differences and friction losses along the lateral. The slight additional cost (5 to 10 percent of total lateral cost) is repaid in higher uniformity and lower operational stress.

9.4 Pressure Regulation and Automation

Operating pressure must be controlled at the emitter to produce uniform discharge. Pressure regulators are installed at the head of each hydraulic zone to limit incoming pressure to the design value (typically 100 to 200 kPa). Self-cleaning models with integrated pressure gauges are increasingly common in commercial Ukrainian installations and dramatically simplify operation.

Automation has progressed rapidly: a modern commercial apple orchard irrigation system typically includes a programmable controller (PLC or dedicated irrigation controller) that operates solenoid valves on a pre-programmed schedule, with sensor inputs from soil moisture probes, flow meters, and pressure switches. Remote operation by GSM or LoRaWAN allows the operator to monitor and adjust the system from a smartphone, including emergency shutdown if a flow or pressure anomaly is detected. The capital cost is modest (1,500 to 4,000 USD for a typical 10–50 ha installation) and pays back through reduced labour and improved reliability.

9.5 Installation Best Practices

Whatever the design, the system's long-term performance depends on installation quality. Common installation problems that can severely compromise an otherwise good design include:

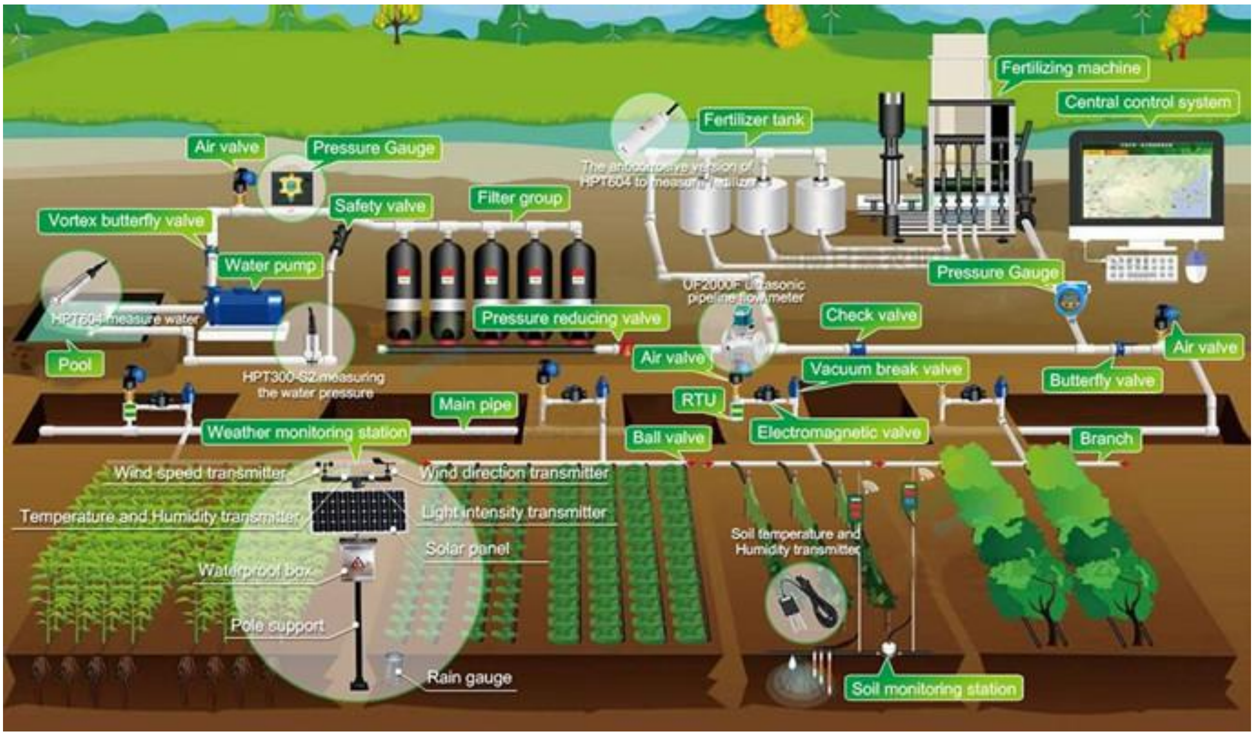


Figure 37 - Installation best practices

- Inadequate trench depth for buried pipework, leading to mechanical damage from cultivation and frost heave in cold winters.
- Imperfectly cleaned or jointed pipe, allowing debris into the system that subsequently clogs emitters.
- Mismatched fittings (different manufacturers, different pressure ratings) producing failures at the joints.
- Inadequate flushing of new pipe before commissioning, leaving manufacturing debris that destroys filters and emitters in the first weeks of operation.
- Insufficient air valves and pressure-relief valves at high points and at the pump discharge.
- Incorrect or absent labelling of valves, making subsequent troubleshooting difficult.

Standard installation practice for a Ukrainian commercial apple orchard drip system includes: pre-installation site marking and verification of tree row geometry; trenching for buried mains at 0.6 to 1.0 m depth (below the frost line); pressure-testing of all buried pipe before backfilling; thorough flushing of the entire main and sub-main network at design flow rate; commissioning of filters with a controlled increase in flow over the first hour; and a 30-day post-installation inspection to identify and correct any defects under warranty.

10 Operation, Maintenance, and Troubleshooting

Most irrigation systems fail not from design defects but from neglected maintenance. A well-designed drip system has a service life of 12 to 20 years; the same system without routine care may degrade to unusable condition in 3 to 5 years. This chapter sets out the routine operational and maintenance practices that protect the investment, and offers a systematic approach to common problems.

10.1 Routine System Checks

A well-managed commercial Ukrainian apple orchard irrigation system has a written maintenance programme with daily, weekly, monthly, and annual tasks. The principal items in a typical programme are:

Daily during the irrigation season:

- Check pump and motor for unusual noise, vibration, or leaks; verify operating pressure at the pump discharge.
- Inspect filter pressure differential and backflush if elevated above set point.
- Verify that the programmed irrigation cycle has run as intended; check log of valve operations.
- Walk one block per day on a rotation to detect leaks, missing emitters, and damaged laterals.

Weekly:

- Read and record soil moisture sensor and rainfall data; review against the scheduling plan.
- Check inlet pressure at the head of each hydraulic zone and compare with design values.
- Inspect injector for proper operation; verify fertigation log against the nutrient plan.
- Walk each block at least once per week during peak demand; verify uniform wetting patterns.

Monthly:

- Flush each lateral by opening the end cap and running the system for 1 to 2 minutes until water runs clear.
- Disassemble, inspect, and clean a sample of emitters (typically 1 percent of total) to detect any clogging trends early.
- Check accuracy of flow meter; record cumulative water use.
- Test all pressure switches, alarms, and automatic shutdowns.

Annually (pre-season and post-season):

- Full system inspection, including pump teardown and motor service.
- Replacement of any laterals or fittings showing UV degradation, mechanical damage, or persistent leakage.
- Acid treatment of laterals (see Section 10.2) to remove mineral deposits.
- Calibration of soil moisture sensors and weather station.

- Review of operational records and irrigation efficiency from previous season.

10.2 Preventing and Resolving Clogging

Clogging of drip emitters is the single most common operational problem. It progresses gradually, often unnoticed until the affected zone shows yield decline or visual stress symptoms; by the time it is severe, the affected emitters may be irreversibly clogged. The three categories of clogging are physical (suspended solids), chemical (mineral precipitates), and biological (algae, bacteria, slime), and each requires different prevention and treatment.

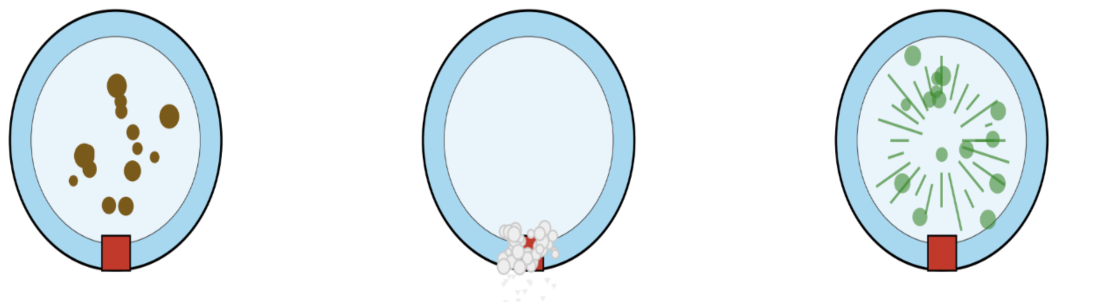


Figure 38 - Three categories of drip emitter clogging (a) physical — suspended particles, requiring filtration upgrade and flushing; (b) chemical — mineral scale (mainly calcium carbonate), requiring acidification; (c) biological — algae and bacterial slime, requiring chlorination and biocide use.

Physical clogging is caused by sand, silt, organic debris, or filter media that has passed downstream of filtration. Prevention requires: appropriately sized filtration for the water source (Chapter 9); regular flushing of laterals; and prompt response to any increase in filter pressure differential. Treatment is mechanical: backflushing the filter, flushing the laterals at high velocity, and — if individual emitters are blocked — physical cleaning or replacement.

Chemical clogging is caused by precipitation of calcium carbonate (the most common in Ukrainian waters), calcium phosphate (from fertigation), iron oxide, and manganese oxide. Prevention requires: water analysis at the design stage; acid injection to maintain pH below 6.5 (typically sulphuric or phosphoric acid for routine treatment, nitric acid for occasional pulse-treatment); and avoidance of incompatible fertiliser combinations. Treatment of established mineral clogging is by acid pulse: an acid solution (typically pH 2–3) is circulated through the system for 30 to 60 minutes, then flushed thoroughly with clear water. This is normally a post-season operation.

Biological clogging is caused by algae, bacterial slime, and the iron-bacteria complexes characteristic of some groundwaters. Prevention requires light-exclusion of water in surface tanks and reservoirs; periodic chlorine shock-treatment (typically 5 to 10 ppm free chlorine for 30 to 60 minutes, then flushing); and avoidance of long stagnant periods. Acidification also suppresses bacterial growth and helps prevent biological clogging. Treatment of established biological clogging is by chlorine pulse at higher concentration (20 to 50 ppm), with full flushing afterwards.

10.3 Winter Season

Ukrainian winters can produce freezing of water in irrigation pipes, with consequent damage from expansion. Winterization is therefore a critical pre-winter task in all orchard regions. A proper winterization sequence includes:

- Apply the final irrigation of the season (the "winter watering"), typically in mid-October, to bring the soil profile to field capacity before freeze-up. This protects roots from desiccation during freeze-thaw cycles.
- Inject acid through the system to maintain pH at 5.5 to 6.0 in the final irrigation event, then flush briefly to clear the lines without removing the residual acid that suppresses biological activity over winter.
- Drain the system. Open all flush valves, drain valves, and lateral end caps; remove water from low points and from the pump and filter assemblies. Compressed-air blow-out is recommended for sub-mains and mains where complete drainage by gravity is not possible.
- Remove and store indoors all easily damaged components: pressure regulators, flow meters, solenoid valves, controllers, sensors. Cover and protect the pump and motor against ice and animal damage.
- Inspect and document the system condition for spring start-up.

Surface drip laterals are usually left in place over winter. They tolerate moderate freezing if fully drained. The principal winter risks are mechanical damage from rodents, hares (which gnaw on plastic), and accidental damage during dormant pruning operations. Inspection in late winter to identify and repair such damage before spring start-up is recommended.

10.4 Common Problems and Solutions

Table 6 summarizes common irrigation problems, their probable causes, and recommended actions, as a quick-reference troubleshooting guide for orchard managers.

Symptom	Probable cause	Recommended action
Low pressure at zone head	Pump worn / pipe leak / closed valve	Inspect pump output, check for leaks, verify valves
High pressure at zone head	Closed downstream valve / scaled regulator	Check zone valves and pressure regulator function
Wet patches across blocks	Buried main leak / lateral split	Locate leak by inspection or flow tracking
Dry trees in middle of row	Clogged emitters / damaged lateral	Flush lateral, replace emitters or section
Trees at row end stressed	Lateral length too long / inadequate flush	Check uniformity, flush regularly, consider PC emitters
Filter clogs rapidly	Source water deteriorated / algae bloom	Test water, install pre-filter or shading
Emitters drip after shutdown	No check valves / no anti-drain emitters	Install check valves, replace with anti-drain emitters
Uniform yellowing despite irrigation	Waterlogging / root disease	Check drainage, dig pit, assess root health
Salt crusts on soil surface	Saline water / inadequate leaching	Test water, plan leaching irrigation
Emitters output declines over years	Mineral scale / biological buildup	Annual acid and chlorine treatments

Table 6 — Troubleshooting matrix for common apple orchard irrigation problems. Most problems have multiple possible causes; systematic investigation following the order shown is recommended.

11 Water Conservation and Sustainability

Figure 39 - Water basin

Water for irrigation is a limited resource in much of Ukraine, with growing competition from urban, industrial, and ecosystem demands, and is increasingly subject to regulatory restriction. Climate change is altering both the supply (rainfall, river flow) and the demand (evapotranspiration) sides of the water balance. Long-term economic viability of apple production therefore requires not only efficient design and operation of irrigation systems but a broader approach to orchard water management — capturing rainfall, reducing evaporation, returning drainage water to use, and adapting to changing climatic conditions.

11.1 Water Use Efficiency (WUE) Metrics

Water use efficiency (WUE) can be defined at several scales, and confusion among these definitions has caused much misunderstanding in irrigation discussions:

- Application efficiency: the fraction of water leaving the source that reaches the root zone (typical values from Table 5).
- Crop water productivity: kilograms of fruit produced per cubic metre of water consumed. Typical values for Ukrainian apple are 8 to 12 kg/m³ for irrigated commercial orchards.
- Economic water productivity: monetary value of fruit produced per cubic metre of water. Strongly influenced by price and variety; typical range 5 to 25 USD/m³ for premium varieties.
- System efficiency: the ratio of beneficial water use (transpiration, productive soil evaporation, leaching needs) to total water applied.

Improvement of any of these metrics is a legitimate conservation objective. The largest gains usually come from increasing crop water productivity — through better matching of irrigation to actual demand, regulated deficit strategies, and improved orchard floor management — rather than from incremental gains in application efficiency. A modest 5 percent gain in WUE applied across the principal Ukrainian apple-producing regions would translate into water savings comparable to the entire annual water budget of a small region.

11.2 Mulching and Cover Crops

Soil evaporation can account for 20 to 40 percent of total ET in a young or open-canopy apple orchard. Reducing this evaporation is the single most accessible water-saving practice. Mulching with organic materials (straw, bark, wood chips) under the tree strips at a depth of 5 to 10 cm reduces soil evaporation by 30 to 50 percent during the peak demand period and offers additional benefits: better soil moisture retention between irrigations, weed suppression, gradual nutrient release, improved soil structure, and a reduction in temperature extremes that promotes root activity. Synthetic mulches (woven polypropylene mats) provide similar evaporation reduction with longer life and complete weed control but at higher cost and without organic-matter benefits.

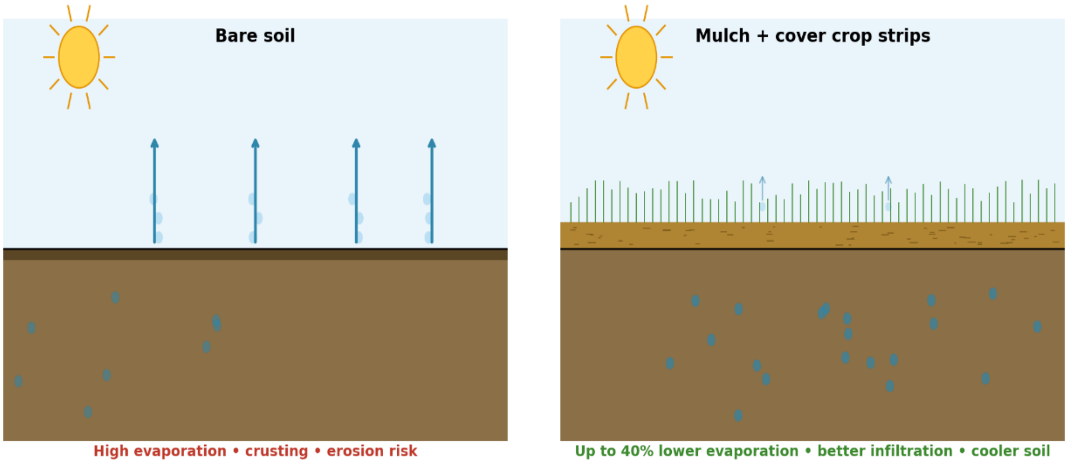


Figure 40 - Comparison of bare soil (left) and mulched/cover-cropped (right) orchard floors. Mulching reduces soil evaporation by 30 to 50 percent during peak ET periods; well-managed cover crops in the alleys provide multiple benefits but compete with trees for water during their active growth.

Cover crops in the alleys between tree rows present a more complex picture. Permanent grass swards stabilise soil, improve trafficability, provide habitat for beneficial insects, and reduce nutrient leaching, but they compete with the trees for water during their growing season — particularly damaging in late spring and early summer in dry years. Best practice for water-limited Ukrainian conditions is a mown grass sward that is allowed to grow only modestly, suppressed by close mowing during the peak ET period and the irrigation strip kept clear (at typical width 1.0 to 1.5 m). Cover crops grown as winter green-manure (cereal rye, vetch, mustard) and incorporated before the main growing season can build soil organic matter and structure without competing for irrigation water. This is an emerging practice in Ukrainian commercial orchards and is being assessed in regional trials.

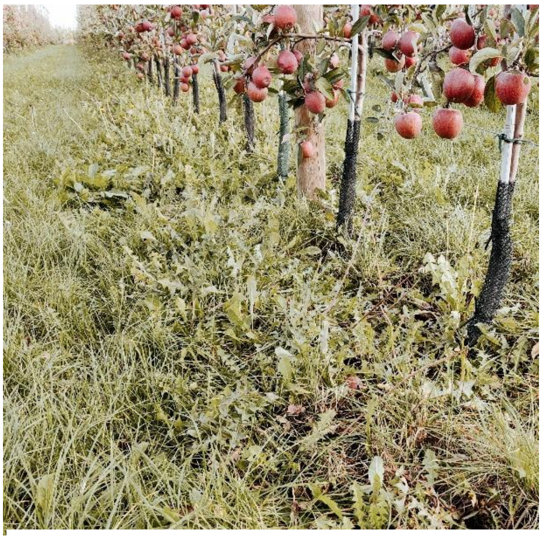


Figure 41 - Covercrops under Apple trees

11.3 Rainwater Harvesting and Reuse

Where the natural water supply is limited, capturing rainfall and snowmelt from the orchard catchment and from associated buildings can substantially augment irrigation supplies. For a 50 ha orchard in central Ukraine, the annual rainfall of approximately 550 mm represents a total water volume of 275,000 m^3; even capturing 5 to 10 percent of this in a storage pond would provide a useful supplementary supply for dry periods. Catchment design considerations include the catchment area, runoff coefficient (typically 0.2 to 0.4 for vegetated orchard floors), pond storage capacity (a function of variability and irrigation demand), and water quality (sediment trapping, biological treatment).

Reuse of drainage water is technically feasible where natural or installed drainage produces collectable flows, but salinity build-up over multiple cycles must be carefully managed. In Ukrainian conditions reuse is most relevant where greenhouse or storage-facility drainage can supplement orchard supply, rather than the recirculation of orchard drainage itself. A pre-feasibility study should always include a full water-quality analysis and a salt-balance calculation for the proposed reuse scheme.

11.4 Drainage

Drainage is the often-overlooked complement to irrigation. Apple trees cannot tolerate prolonged saturation, and irrigation systems that operate without adequate drainage will eventually waterlog at least parts of the orchard. The principal drainage considerations are:

- Natural drainage: assess by post-rain ponding patterns, by digging inspection pits, and by monitoring the watertable. Where the natural drainage is satisfactory (drop of 50 cm in 24 hours in a pit test, no perched watertable in the rooting zone), no installed drainage is needed.

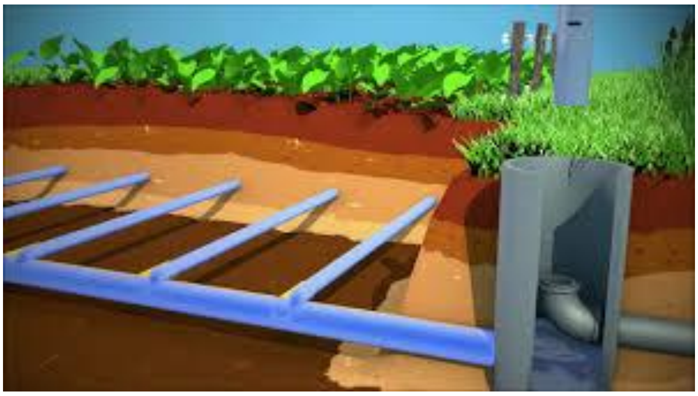


Figure 42 - Schematic image of Drainage

- Surface drainage: contour-grading, swales, and outlet ditches manage excess surface water from heavy rainfall events; essential on flat sites prone to ponding.
- Subsurface drainage: tile drains at 0.8 to 1.2 m depth and 15 to 25 m spacing are standard for heavier soils where the watertable approaches the root zone during wet periods. Modern PVC perforated drains with geotextile envelopes are widely used.
- Drainage maintenance: drains require periodic inspection (the outlet must be functional and not blocked by sediment or vegetation) and occasional flushing.

Climate change projections for Ukraine indicate that summer rainfall events may become less frequent but more intense. Drainage capacity should be sized for projected design events rather than historical averages, particularly in new installations expected to operate for 20 or more years.

11.5 Climate Change Adaptation

The climate of Ukrainian apple-growing regions is changing measurably. The forest-steppe and steppe regions have experienced an increase in mean annual temperature of approximately 1.5 to 2.0 °C over the past 50 years, with the principal increases in winter and early spring; rainfall totals have changed modestly but the distribution has become more variable, with longer dry periods punctuated by more intense events. Projections for the next 30 years indicate further warming of 1 to 2 °C and a continued shift in rainfall distribution.

The implications for apple irrigation are significant:

- Increased growing-season ETo (estimated 5 to 15 percent over the next 30 years), increasing irrigation demand.
- More variable rainfall, increasing the value of irrigation as a buffer and shifting the balance toward higher-capacity, more flexible systems.
- Earlier bud break and bloom, increasing exposure to late spring frosts in some regions and potentially shifting the timing of peak water demand.
- Higher summer temperatures, increasing the risk of sunscald and bitter pit, and increasing the value of overhead cooling sprinklers in premium plantings.
- Possible changes in suitable production regions, with some southern steppe regions becoming marginal without expanded irrigation, and some northern regions becoming more productive.

Adaptation strategies for the irrigation system include: sizing new installations for the projected demand 15 to 20 years hence rather than current values; investing in flexible automation that can respond rapidly to changing conditions; expanding water storage to buffer increasingly variable supply; and explicitly designing for water-conservation strategies (RDI, mulching, cover crops) as core practices rather than emergency measures.

12 Economic and Regulatory Aspects

Irrigation is a major capital investment and a continuing operating cost. The decision to install or upgrade a system should be supported by a sound economic analysis that captures both the costs and the benefits in monetary terms over the life of the orchard. This chapter outlines the principal economic considerations and discusses energy use — typically the largest single operating cost — in some detail.

12.1 Cost-Benefit Analysis of Irrigation Systems

A standard cost-benefit analysis for an apple irrigation system considers:

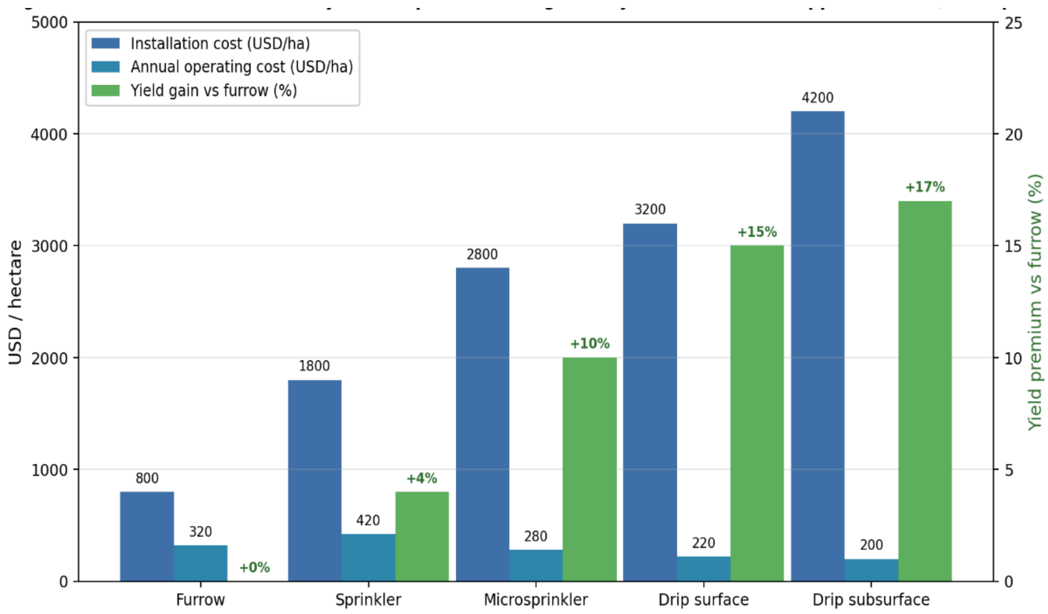


Figure 43 - Indicative cost for the principal irrigation systems in commercial Ukrainian apple production.

- Capital investment: pump, filter, mains, sub-mains, laterals, emitters, control system, installation labour. Typical values for a 10 ha commercial drip installation in Ukraine in 2023 conditions range from 35,000 to 55,000 USD, or 3,500 to 5,500 USD/ha. Microsprinkler systems and overhead frost-protection systems add 1,000 to 3,000 USD/ha each.
- Annual operating costs: energy, water (where charged), maintenance and repair (typically 3 to 6 percent of capital cost annually), filter media and consumables, and labour for operation and maintenance (typically 5 to 15 hours per hectare per year).
- Annual benefits: incremental yield over rainfed (typically 15 to 40 t/ha additional fruit in commercial Ukrainian conditions, depending on region and variety), improved fruit quality (size, colour, dry matter, storage life), reduced biennial bearing, and risk reduction in dry years.
- Indirect benefits: fertigation efficiency, frost protection (where applicable), feasibility of high-density planting that would not be reliable without irrigation. Payback periods for new commercial irrigation systems in Ukrainian apple production typically range

from 3 to 6 years for drip systems on suitable sites, 4 to 8 years for microsprinklers, and longer for overhead systems whose value derives largely from frost protection in specific years. These payback figures are highly sensitive to local market prices and to the variety of apple grown; premium varieties for fresh export typically pay back faster than industrial-grade varieties.

Risk-related benefits should be included in the analysis but are often neglected because they are harder to quantify. In a dry year without irrigation, yield losses of 40 to 70 percent are typical in Ukrainian steppe conditions and 15 to 30 percent in the forest-steppe. The avoided losses in such years constitute a substantial fraction of the total benefit of irrigation, and a risk-aware analysis includes them.

12.2 Energy Use and Pumping Costs

Energy use is the principal operating cost of pressurised irrigation systems and is dominated by the pump power required to deliver water at the design flow rate and head. The basic relationship is:

Pump power (kW) = (Flow rate (L/s) × Total dynamic head (m) × 9.81) / (1000 × Pump efficiency)

For a typical 10 ha drip system with peak flow of 12 L/s and total dynamic head of 50 m (combining 30 m static lift, 10 m friction loss, and 10 m required operating pressure), at a pump efficiency of 70 percent, the required shaft power is approximately 8.4 kW. With electric motor efficiency of 90 percent, the electrical demand is approximately 9.3 kW. Over a full season of 800 hours of operation, total energy consumption is approximately 7,500 kWh, or 750 kWh per hectare.

At 2023 Ukrainian agricultural electricity tariffs (which vary significantly by region and time of day), this represents approximately 100 to 200 USD per hectare per year in electricity costs alone. Diesel pumping is several times more expensive per kWh and is used principally for backup or where grid connection is unavailable.

Strategies for reducing energy consumption in irrigation systems include:

- Pump-system matching: selecting a pump whose efficiency peak coincides with the actual operating point; oversized or undersized pumps waste energy throughout their lives.
- Variable frequency drives (VFDs): allowing the pump speed to be matched to actual demand, with energy savings of 20 to 40 percent compared with throttled operation.
- Time-of-day operation: shifting irrigation to off-peak electricity hours where tariff differentials apply.
- Pressure reduction: any reduction in operating pressure compatible with uniformity reduces energy use proportionally; pressure-compensating emitters and low-pressure designs save energy throughout their lives.
- Solar PV integration: increasingly viable in Ukrainian conditions for daytime irrigation, particularly where peak irrigation coincides with high solar production.

Water charges, where applied, vary by region and by water source. Surface water from state hydrotechnical networks may be subject to volumetric charges; groundwater from private wells is typically subject only to extraction permitting and possibly a quota on annual abstraction. Regulatory frameworks for water use in Ukrainian agriculture have evolved substantially over the past decade and a current review of obligations is recommended for any new installation.

In sum, the total annual cost of irrigation operation in a 10 ha drip-irrigated Ukrainian apple orchard typically falls in the range of 600 to 1,500 USD/ha (energy, water, maintenance, labour combined), against incremental gross returns of 4,000 to 12,000 USD/ha from the additional yield and quality of the irrigated crop. The returns are clearly attractive in any reasonable scenario, but they require competent design, operation, and maintenance to be realised.

Appendix

The appendices in this section collect conversion tables, quick-reference Kc values, water quality guidelines, a design worksheet, and a glossary of terms for ready use in the field.

Appendix A — Unit Conversions and Useful Constants

Conversions among the units commonly used in irrigation work:

From	To	Multiply by
mm of water per ha	m^3 per ha	10
mm of water per ha	L per m^2	1
m^3 per h	L per s	0.278
L per s	m^3 per h	3.6
kPa (pressure)	m of water head	0.102
m of water head	kPa	9.81
bar	kPa	100
psi	kPa	6.895
hectare	m^2	10,000
ha-mm	m^3	10
Wh	J	3,600
kWh	MJ	3.6
MJ/m^2/day (radiation)	mm/day (ET equiv.)	0.408

Table A.1 — Common unit conversions used in irrigation calculations.

Useful physical constants and rules of thumb:

- Latent heat of vaporisation of water at 20 °C: 2.45 MJ/kg.
- Density of water at 20 °C: 998 kg/m^3.
- Specific heat of water: 4.186 kJ/kg/°C.
- Approximate radiation conversion: 1 MJ/m^2/day produces 0.408 mm/day equivalent ET.
- Approximate temperature conversion: ETo rises by about 5–7 percent per 1 °C increase in mean temperature.
- 1 atm = 101.3 kPa = 1.013 bar = 10.33 m water column = 14.7 psi.

Appendix B — Apple Crop Coefficient (Kc) Quick Reference

Recommended Kc values by growth stage and orchard age, condensed from Chapter 4 for quick reference. These values assume drip or microsprinkler irrigation, bare or lightly mulched tree strips, and managed grass alleys.

Days after bud break	Stage	Y1	Y2	Y3	Y4	Y5+
0–25	Bud break/bloom	0.30	0.40	0.50	0.60	0.70

25–55	Petal fall/fruit set	0.35	0.50	0.65	0.75	0.85
55–95	Cell division	0.40	0.55	0.75	0.90	1.05
95–135	Cell expansion	0.45	0.60	0.80	1.00	1.15
135–165	Pre-harvest	0.40	0.55	0.75	0.90	1.05
165+	Post-harvest	0.30	0.40	0.50	0.55	0.65

Table B.1 — Apple Kc quick reference by orchard age and days after bud break, Ukrainian conditions.

Appendix C — Irrigation Water Quality Guidelines

Standard guidelines for irrigation water quality assessment for apple in Ukrainian conditions, summarised from FAO and regional sources. These values are starting points; site-specific interpretation may revise them in particular contexts.

Parameter	No restriction	Slight–moderate	Severe
Electrical conductivity (dS/m)	< 0.7	0.7–1.5	> 1.5
Sodium adsorption ratio (SAR)	< 3	3–9	> 9
Chloride (mg/L)	< 140	140–350	> 350
Sodium (mg/L)	< 70	70–200	> 200
Boron (mg/L)	< 0.5	0.5–2.0	> 2.0
Bicarbonate (mg/L)	< 90	90–520	> 520
Iron (mg/L)	< 0.2	0.2–1.5	> 1.5
pH	6.5–8.4	< 6.5 or > 8.4	extreme
Suspended solids (mg/L)	< 50	50–100	> 100

Table C.1 — Irrigation water quality guidelines for apple, adapted from FAO and regional sources.

Appendix D — Design Worksheet for a Drip System

The following worksheet steps lead from agronomic inputs to a basic design for a drip irrigation system. It is intended for preliminary design and for evaluating supplier proposals; final design should be performed using calibrated software and verified by an experienced irrigation engineer.

Step 1 — Site and agronomic data:

- Orchard area (ha): ________
- Tree spacing (m × m): ________
- Number of trees per hectare: ________
- Peak monthly ETo (from Table 4.1, mm/day): ________
- Peak Kc (from Table 4.2, dimensionless): ________

- Peak ETc = ETo × Kc (mm/day): _______

Step 2 — System sizing:

- Application efficiency (typically 0.92 for drip): _______
- Gross peak demand = ETc / efficiency × safety factor (1.15) (mm/day): _______
- Daily gross volume = gross peak × area × 10 (m^3/day per ha × ha): _______
- Hours of operation per day (typically 16–18): _______
- System flow rate = daily volume / hours (m^3/h): _______
- Convert to L/s = m^3/h × 0.278: _______

Step 3 — Zone planning:

- Number of hydraulic zones (typically 3–6): _______
- Flow per zone = system flow / zones: _______
- Area per zone = total area / zones: _______

Step 4 — Lateral design:

- Emitter type and discharge (L/h): _______
- Emitter spacing (m): _______
- Number of emitters per tree: _______
- Volume per tree per hour = emitter discharge × emitters per tree (L/h): _______
- Volume per tree per day = above × hours of operation (L/day): _______

Step 5 — Pump and filtration:

- Required pump flow (L/s): from Step 2
- Total dynamic head = static lift + friction + emitter pressure (m): _______
- Pump power (kW) = flow (L/s) × TDH (m) × 9.81 / (1000 × efficiency): _______
- Filter type (sand / disc / screen): _______
- Filtration rating (mesh / micron): _______

Appendix E — Glossary of Terms

- Available water (AW): The soil water held between field capacity and permanent wilting point that is available for plant uptake.
- Crop coefficient (Kc): A dimensionless ratio that adjusts reference evapotranspiration to a specific crop and growth stage.
- Crop evapotranspiration (ETc): The combined loss of water from soil evaporation and plant transpiration in a specific crop under specific conditions.
- Deficit irrigation: A strategy of supplying less water than full ETc, applied seasonally or at specific growth stages, to save water or improve product quality.
- Drip irrigation: A pressurised irrigation system delivering water at low rates through emitters placed near plant root zones.
- Effective rainfall: The fraction of total rainfall that contributes to crop water supply, after accounting for runoff, deep percolation, and canopy interception.
- Emitter: A device that discharges water from an irrigation lateral at a controlled, low rate.
- Evapotranspiration (ET): The combined process of evaporation from soil surfaces and transpiration from plants.
- Fertigation: The application of fertilisers dissolved in irrigation water.

- Field capacity (FC): The water content of a soil after free drainage has ceased, typically 24 to 48 hours after thorough wetting.
- Hydraulic zone: A subdivision of an irrigation system that is operated as a single unit, typically with a single valve and a defined flow rate.
- Microsprinkler: A small spray emitter that distributes water in a circular or sector pattern, typically operating at low pressure with a wetted radius of 1.5 to 3 m.
- Pressure-compensating emitter: An emitter designed to maintain a constant discharge across a range of operating pressures, used to ensure uniformity on sloping ground or long laterals.
- Reference evapotranspiration (ETo): The evapotranspiration rate from a hypothetical reference grass surface, used as a climatic index of water demand.
- Regulated deficit irrigation (RDI): A controlled deficit irrigation strategy applied during specific stress-tolerant growth phases.
- Stem water potential (Ψstem): A measure of the water status of a plant, expressed in MPa, with more negative values indicating greater water stress.
- Subsurface drip irrigation (SDI): Drip irrigation with laterals buried below the soil surface.
- Tensiometer: An instrument for measuring soil matric potential, expressed in centibars or kilopascals.
- Transpiration: The loss of water vapour from plants, principally through stomata in leaves.
- Water use efficiency (WUE): A measure of the ratio of crop output (yield or value) to water input.
- Wilting point (WP): The soil water content at which plants can no longer extract water and wilts permanently, conventionally at a matric potential of −1.5 MPa.

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The following sources provide further reading on the technical, agronomic, and management aspects of apple irrigation discussed in this manual. Sources are grouped thematically and include standard international references, regional Ukrainian and East European technical literature, and selected scientific papers of direct practical relevance.

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	Module OB02: Soil science: soil analysis, basic principles of fertilisation and setting up equipment for fertilisation in fruit growing
	Module OB03: Plant protection technology: Adjusting equipment for the application of plant protection products on fruit crops. Calculating the dosage
	Module OB04: Irrigation in fruit growing. Calculation of water requirements. Fertigation for apple trees
	Module OB05: Comprehensive control of diseases and pests in apple tree cultivation
	Module OB06: Pruning in apple orchards. Shaping the apple tree canopy on M9 rootstock
	Module OB07: Protection of orchards against frost
	Module OB08: Organisation of the apple harvest
Vegetable growing (GB)	Module GB01: Planning and cultivation of 'borscht vegetables' (onions, carrots, beetroot)
	Module GB02: Sowing 'borscht vegetables' (onions, carrots, beetroot); adjusting the seed drill
	Module GB03: Irrigation in vegetable growing. Calculating water requirements. Fertigation for the cultivation of 'borscht vegetables' (onions, carrots, beetroot)
	Module GB04: Disease control in 'borscht vegetables' (onions, carrots, beetroot, white cabbage)
	Module GB05: Pest control for 'borscht vegetables' (onions, carrots, beetroot, white cabbage)
	Module GB06: Organisation of the harvest of 'borscht vegetables'
Cross-cutting / Comprehensive Topics (UT)	Module UT01: Preparing storage facilities for the apple harvest season. Storing apples
	Module UT02: Preparing storage facilities for the cabbage harvest season. Storing cabbage
	Module UT03: Economics of vegetable growing: profitability, planning and analysis of operations
	Module UT04: Economics of fruit growing: economic aspects, operational planning and analysis
	Module UT05: Quality assurance of fruit produce during storage
	Module UT06: Quality assurance of raw vegetable materials during storage
	Module UT07: Energy-efficient technologies for the storage and initial processing of fruit and vegetables
Plant protection in organic fruit and vegetable production (OEK)	Module OEK01: Disease and pest control in organically grown vegetables
	Module OEK02: Disease and pest control in organic fruit production

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