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

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Lehrmodule DUALOG (Skript)

MODUL GB03

Irrigation of Vegetables

Red Beet, Carrot, Onion, White Cabbage – A Practical Field Manual for Ukrainian Vegetable Growers

Implementiert von: GFA Consulting Group, Generalbeauftragte des BMLEH Büro Berlin; ADT Project Consulting

Operative Partner Ukraine:

Introduction

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 of Vegetables"

This module describes, in a concise and practical manner, the principles and field operations of **irrigation** and **fertigation** for the four classic borscht vegetables – red beet, carrot, onion, and white cabbage. It brings together crop water requirements, soil and climatic factors, irrigation system selection, scheduling, fertigation programmes, system design, operation and maintenance, and the economics of irrigation investment under Ukrainian conditions. Worked examples, decision tables, and field-ready schedules are provided throughout to make the manual directly usable in advisory work and on-farm practice.

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1. Introduction

1.1 Importance of Irrigation in Vegetable Production

Water is the most influential single input in vegetable production. In Ukraine, the same hectare of cabbage that produces 30 t·ha^{-1} in rain-fed conditions of a dry summer can produce 60–70 t·ha^{-1} when properly irrigated, with no other change in cultivation practice. Onion, carrot, and red beet show comparable responses. In the Kherson Steppe and surrounding southern regions, where the rainfall sum from June to August (the period of maximum crop water demand) averages 110–140 mm, growing vegetables without supplemental irrigation is technically possible but commercially unwise.

The Kakhovka irrigation system – the largest in Europe – historically delivered water to roughly 220 000 ha of farmland in Kherson Oblast alone, demonstrating both the scale of the irrigation challenge in Ukraine and the long-standing recognition that organized irrigation is essential. After damage to parts of the network, regional water-use planning has shifted toward smaller, decentralized, high-efficiency systems such as drip and micro-sprinkler installations operated at the farm level.

Table 1 - Why irrigate vegetables in Ukraine?

Driver	Effect on production
Low summer rainfall in Steppe zone	350–500 mm/yr total; only ~30–40% falls in the growing season
High summer ETo	5–7 mm/day in July; demand far exceeds supply on most days
Climate-change projections	Hotter summers, more variable rainfall (RCP 4.5 / RCP 8.5 scenarios show widening deficits)
Sensitivity of vegetables to stress	Even short drought during head- or bulb-formation reduces marketable yield 20–60%
Profitability of vegetables	High value crops repay irrigation investment within 1–3 seasons

1.2 Overview of Vegetable Water Requirements

Vegetable crops are physiologically and economically demanding water users. They are mostly shallow-rooted, have a high leaf-area index at maturity, and are harvested in the fresh state where water status during the final two weeks before harvest directly determines visual quality. For the four borscht vegetables, typical seasonal water requirements (evapotranspiration, ETc) in Ukrainian conditions are summarized in Table 2 below.

Table 2 – Typical seasonal water requirements of borscht vegetables in central and southern Ukraine.

Crop	Growing season (days)	Seasonal ETc (mm)	Critical period
Onion (Allium cepa)	110–150	450–550	Bulb formation (June–July)
Carrot (Daucus carota)	120–180	400–500	Root thickening (June–July)
Red beet (Beta vulgaris)	90–120	350–500	Root enlargement (July–Aug)
White cabbage (Brassica oleracea)	120–180	400–550	Head formation (July–Aug)

These figures represent ETc under non-limiting soil-water conditions. The actual irrigation water requirement (IWR) is the part of ETc not satisfied by rainfall and stored soil water, increased to compensate for application losses. A typical southern-Ukrainian onion crop, with effective in-season rainfall of 90 mm and an application efficiency of 85 %, would therefore need (500 – 90) / 0.85 ≈ 480 mm of irrigation water.

1.3 Objectives and Scope

This manual is written for Ukrainian growers and extension agents responsible for cabbage, carrot, beet and onion production at the small-to-medium commercial scale (0.5–50 ha). Its objectives are:

- To explain how water moves through the soil-plant-atmosphere system in terms a non-specialist can act on.
- To provide stage-specific water requirements, crop coefficients and tensiometer thresholds for each of the four borscht vegetables.
- To compare furrow, sprinkler and drip irrigation in terms of efficiency, cost and suitability for Ukrainian conditions.

- To set out fertigation programmes that integrate nitrogen, phosphorus, potassium, calcium, magnesium and micronutrients with water delivery.
- To explain how to design, install, operate, and maintain a drip system, and to troubleshoot the problems that most often arise.
- To outline water-conservation strategies (mulching, deficit irrigation, rainwater harvesting) appropriate to the southern Ukrainian Steppe.
- To address the economics of irrigation – capital, pumping energy, and the payback period under typical Ukrainian price conditions.

The manual is deliberately concise. Each chapter ends with a summary table, a worked example, or a decision rule that the user can apply directly in the field.

Table 3 – for whom and how to use this manual.

Reader	**Most useful chapters**
Field grower	Chapters 3, 7, 8, 9, 11
Agronomist / extension agent	Chapters 2, 5, 7, 8, 9
Irrigation designer	Chapters 6, 10, 13
Trainer / student	All chapters in sequence
Policy / financing officer	Chapters 12, 13, References

2. Vegetable Plant Physiology and Water Needs

2.1 Root System Structure and Depth by Crop Group

The rooting depth of a vegetable crop controls the volume of soil that can be tapped for water and nutrients, and therefore the maximum irrigation interval that the crop will tolerate. The four vegetables differ markedly in this respect: onion is the shallowest-rooted of the group, with the bulk of fibrous roots in the upper 25–30 cm of the profile, whereas carrot has a long taproot that can reach 80–100 cm in deep, well-structured soils. Red beet and cabbage are intermediate, with effective rooting depths of roughly 50–70 cm under good management.

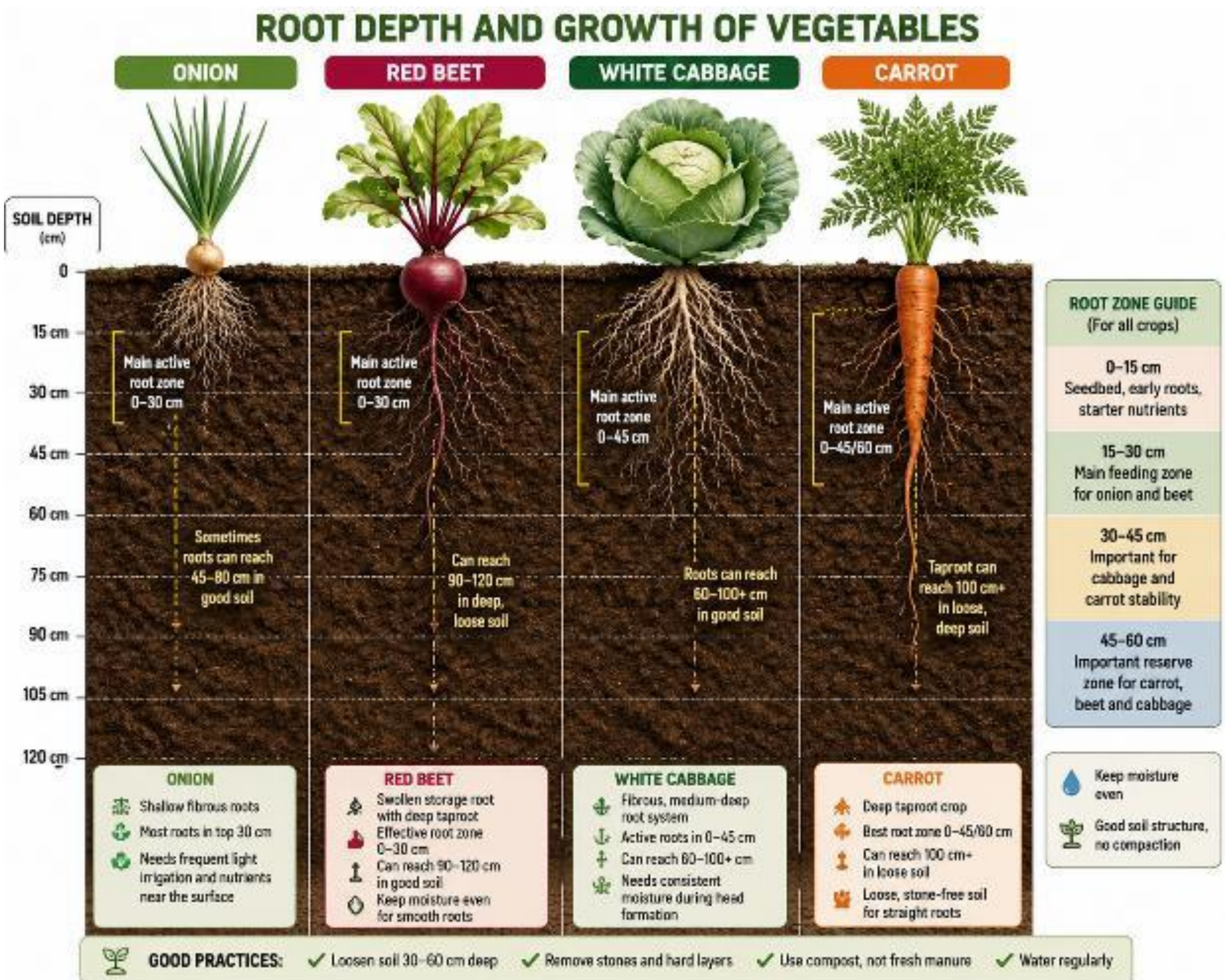

Figure 1 - Root depth and growth of vegetables

Table 4 - Effective rooting depth, root architecture, and irrigation implications.

Crop	Effective root depth (cm)	Root type	Irrigation implication
Onion	25–45	Shallow, fibrous, sparse	Must irrigate frequently and lightly; never let topsoil dry
Cabbage	40–60	Branched taproot + dense laterals	Moderate intervals; bulk of water from 0–40 cm
Red beet	60–90	Strong taproot, lateral branches	Tolerates longer intervals; deeper wetting acceptable
Carrot	60–100	Single, dominant taproot	Soil must be loose and stone-free; avoid splitting from rewetting

2.2 Transpiration and Water Uptake

Plants take up water through their roots and release more than 95 % of it back to the atmosphere through transpiration. The energy that drives transpiration comes from solar radiation, while the rate is modulated by air humidity, wind speed, and stomatal aperture. Soil evaporation is the second component of the water lost from a cropped field. Together these two losses form crop evapotranspiration (ETc), the quantity that irrigation must replace.

Table 5 – Order-of-magnitude daily water uptake (mm/day) for a mature crop on different weather days.

Crop	Cool day (Tmax 18 °C)	Mild day (24 °C)	Warm day (30 °C)	Hot windy day (35 °C)
Onion	1.5–2.0	3.0–3.5	4.5–5.0	6.0–7.0
Carrot	1.5–2.0	2.5–3.0	4.0–4.5	5.5–6.5
Red beet	1.5–2.0	2.5–3.5	4.0–5.0	5.5–6.5
White cabbage	1.8–2.2	3.0–4.0	5.0–6.0	7.0–8.0

2.3 Critical Growth Stages and Water Demand

2.3.1 Germination and Seedling Establishment

During the initial phase, water demand is low (3–4 mm/day) but the soil surface must remain consistently moist. Onion seed is particularly slow to germinate (10–18 days at 15 °C) and is highly sensitive to crusting. Cabbage and red beet seedlings tolerate brief drying once two true leaves have appeared, but should still be kept above 60 % of field capacity in the seedbed.

2.3.2 Vegetative Growth

From four true leaves until the crop covers the ground, the leaf area expands rapidly and water demand climbs from 30 % to 90 % of full ETc. Water stress during this phase reduces final yield more or less linearly: a 30 % deficit at this stage typically reduces marketable cabbage head weight by 20 % at harvest.

2.3.3 Flowering and Pollination

Onion, carrot, red beet, and cabbage are biennials and do not normally flower in their commercial year. Water management in their commercial cycle therefore concentrates on the vegetative and storage-organ phases, not on flowering.

2.3.4 Bulb / Head / Root Development

This is the single most water-sensitive phase. For onion it corresponds to bulb formation (40–80 days after transplanting); for cabbage to head-firming (40–80 days after transplanting); for carrot and beet to root enlargement (30–70 days after thinning). Water stress during this phase causes splitting, hollow heart, premature bolting, and small marketable size – losses that cannot be recovered later in the season.

2.3.5 Maturation and Harvest

Water demand falls sharply in the final 10–20 days of the cycle. For onion, irrigation must be terminated about two weeks before harvest to allow neck-drying for storage. Cabbage and root crops are less sensitive but still benefit from reduced last-week applications to firm up tissue.

Table 6 – Approximate distribution (%) of total seasonal water demand across crop growth stages.

Stage	**Onion**	**Carrot**	**Red beet**	**Cabbage**
Establishment	10–20 %	10–15 %	5–10 %	5–15 %
Vegetative	15–25 %	10–20 %	10–20 %	15–25 %

Stage	Onion	Carrot	Red beet	Cabbage
Bulb / root / head formation	30–55 %	25–40 %	20–35 %	30–50 %
Maturation	5–15 %	5–15 %	5–10 %	5–15 %

2.4 Water Stress: Symptoms and Effects on Yield and Quality

Detecting water stress early is one of the most valuable field skills a vegetable grower can develop. Stress signs become visible only after substantial damage has already been incurred, but a daily walk through the field, especially during the hottest part of the day, can catch problems while they are still correctable.

Tabel 1 – Visible symptoms of water stress in vegetables – early to late.

Crop	Early symptoms → late symptoms
Onion	Bluish-green tip discoloration → leaf-tip drying → bulb size reduction, premature bulbing
Carrot	Foliage darkening, slight wilt at midday → root cracking on rewetting → forked or small roots
Red beet	Leaf-margin reddening intensifies → midday wilt → zoning rings in flesh, hollow heart
White cabbage	Outer leaves cup downward → wilting at midday → loose heads, tipburn from Ca deficit

In addition to direct yield loss, water stress can damage product quality in ways that the buyer notices long before the agronomist does. Onion neck rot, carrot splitting, beet zoning rings, and cabbage tipburn are all forms of stress-induced quality loss. Each of them has a more or less direct link to either a single severe stress event or to repeated wet-dry cycles, both of which can be avoided by proper irrigation scheduling.

Tabel 2 – Quality defects caused by irrigation problems.

Defect	**Crop**	**Underlying cause**
Splitting / cracking	Carrot, beet, cabbage	Heavy irrigation after dry period; sudden rewetting
Tipburn	Cabbage	Erratic water supply → impaired Ca translocation to inner leaves
Bolting	Onion, beet, cabbage	Drought stress + cold shock during seedling phase
Neck rot	Onion	Late-season over-irrigation; high humidity at bulb maturation
Hollow heart	Beet, large cabbage	Rapid late growth following deficit; potassium deficiency
Small marketable size	All	Cumulative deficit during the storage-organ phase

3. Vegetable Crop Groups and Their Specific Water Requirements

3.1 Leafy Vegetables

Leafy vegetables (lettuce, spinach, chard) are characterised by shallow roots, dense canopies, and continuous harvest cycles. Their seasonal water requirement is moderate (250–400 mm), but the demand is concentrated in a short cycle (35–80 days). Water stress causes immediate quality loss – limp leaves, bitterness, premature bolting. Drip or low-volume sprinkler is preferred; furrow irrigation is rarely used because of disease risk on the wet canopy.

Tabel 3 – Reference water requirements for leafy vegetables.

Crop	Season (days)	ETc (mm)	Critical period
Lettuce	60–90	240–350	Heading
Spinach	35–60	180–250	Leaf expansion
Swiss chard	60–100	300–400	Continuous

3.2 Fruiting Vegetables

Tomato, pepper, eggplant, and cucumber make up the fruiting vegetables. Their seasonal water requirement is high (500–800 mm), concentrated in the fruit-bearing phase. Drip with fertigation is the dominant system worldwide for these crops, often combined with plastic mulch and protected cultivation.

Tabel 4 – Reference water requirements for fruiting vegetables.

Crop	Season (days)	ETc (mm)	Critical period
Tomato (field)	130–180	550–800	Fruit set & enlargement
Pepper	120–180	500–700	Fruit set
Eggplant	130–170	500–700	Flowering
Cucumber (field)	70–110	350–500	Fruiting

3.3 Root and Tuber Crops (Carrot, Red Beet)

Carrot and red beet are the two root crops. Both are slow to establish, require finely textured but loose soil, and respond strongly to consistent water supply during root enlargement. Polish field trials covering the period 1991–1999 on light sandy soils showed that drip-irrigated red beet stabilised at over 20 $t \cdot ha^{-1}$ every year, whereas non-irrigated plots produced between 0.87 and 21.4 $t \cdot ha^{-1}$ depending on rainfall. The same studies identified July as the most critical month for irrigation effectiveness.

The relationship between July rainfall and red-beet yield increase from sprinkler irrigation, derived from multiple years of field data, can be expressed by the linear model $Q = 1.77 \times (190 - P)$, where Q is yield increase in $dt \cdot ha^{-1}$ and P is real precipitation in July–August in mm. Comparable Polish regression equations for carrot ($Q = 2.94 \times (242 - P)$) and celeriac ($Q = 1.77 \times (190 - P)$) confirm that the rate of yield gain per mm of irrigation is highest in carrot, intermediate in beet, and lower in cabbage.

Tabel 5 – Carrot growth stages and stage-based Kc (FAO-56).

Stage	Length (days)	Kc	Daily ETc (mm)	Cumulative ETc (mm)
Initial	20–30	0.7	1.5–2.5	30–50
Development	30–50	0.7–1.05	2.5–4.5	100–200
Mid-season	30–60	1.05	4.5–6.0	220–340
Late	20–30	0.95	3.0–4.0	70–110
Total	100–170	—	—	420–700

Source: FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1998).

Tabel 6 – Red beet growth stages and stage-based Kc (FAO-56, table beet).

Stage	Length (days)	Kc	Daily ETc (mm)	Cumulative ETc (mm)
Initial	15–25	0.5	1.0–2.0	20–40
Development	25–35	0.5–1.05	2.5–4.5	90–160
Mid-season	20–40	1.05	4.5–6.0	150–260

Stage	Length (days)	Kc	Daily ETc (mm)	Cumulative ETc (mm)
Late	10–20	0.95	3.0–4.0	40–80
Total	70–120	—	—	300–540

3.4 Brassicas (White Cabbage)

White cabbage is the principal brassica in Ukrainian vegetable production. Indian field experiments on cabbage variety C-139 across three consecutive seasons showed that drip irrigation scheduled at 80 % of ET, applied once every two days, gave the best combination of yield (up to 70 t·ha^{-1}) and water-use efficiency. Drip systems also saved 30–40 % of fertilizer compared to surface irrigation while improving quality and reducing salt accumulation in the root zone.

Tabel 7 – Cabbage growth stages and irrigation guidelines.

Stage	Days	Kc	Irrigation note
Establishment	0–20	0.7	Keep transplant root ball moist; light daily irrigation
Head initiation	20–50	0.85–1.0	Increase frequency; never allow stress
Head firming	50–90	1.05	Peak demand 5–6 mm/day; do not skip
Maturation	90–120	0.95	Reduce gradually; helps storability

3.5 Alliums (Onion)

Onion is the most demanding of the borscht crops in irrigation terms. Its shallow root system, slender leaves, and high marketable-yield sensitivity to soil-water tension combine to make precise irrigation management essential. Treasure Valley (Oregon, USA) trials over more than two decades have established that drip-irrigated onion produces maximum bulb size and profit when the soil-water tension at the 20-cm depth is held close to 20 kPa (cb) on silt-loam soil. Wetter conditions promote disease in storage; drier conditions reduce bulb size.

In Ethiopian semi-arid conditions, lysimeter measurements of the Nafis onion variety gave a seasonal ETc of 460 mm with stage-based Kc values of 0.68 / 0.89 / 1.03 / 0.86 for the initial, development, mid-season, and late-season stages, respectively. These values are useful reference points for Ukrainian conditions, though local validation is encouraged.

Tabel 8 – Onion stage-based Kc and ETc (Nafis variety, lysimeter data).

Stage	Days after transplanting	Kc	Daily ETc (mm/day)	Stage total (mm)
Initial	1–25	0.68	3.12	78
Development	25–55	0.89	4.19	126
Mid-season (bulb)	55–85	1.03	4.81	144
Late season	85–110	0.86	3.84	96
Whole season	1–110	—	—	460

Practical conclusion: *onion requires irrigation every 1–3 days under drip systems in* *mid-summer Ukrainian conditions, with each event delivering 5–15 mm. Long, infrequent applications are unsuitable.*

3.6 Legumes

Legumes (bean, pea) if they are included in vegetable rotations both for their direct value and for their nitrogen-fixing contribution to the following crop. Seasonal ETc is moderate (300–500 mm). Critical periods are flowering and pod-fill; water stress at these stages is the single largest cause of yield loss. Drip irrigation is ideal because it keeps the canopy dry and reduces the risk of foliar diseases such as bean rust and powdery mildew.

Tabel 9 – Reference water requirements for legumes.

Crop	Season (days)	ETc (mm)	Critical period
Dry bean	90–130	300–500	Flowering, pod-fill
Snap bean	60–90	250–400	Flowering, pod-fill
Garden pea	65–100	300–450	Flowering

4. Soil and Site Considerations

4.1 Soil Texture and Water-Holding Capacity

Soil texture – the proportions of sand, silt, and clay – determines how much water the soil can hold and how readily that water is given up to the crop. Sandy soils hold little water and drain quickly; clay soils hold a great deal of water but can become waterlogged and difficult to wet uniformly. The medium-textured loams and silt-loams of central Ukraine and the chernozems of the Forest-Steppe are ideal substrates for vegetable production.

Tabel 10 – Soil texture, infiltration rate, and available water capacity.

Texture	Infiltration (mm/h)	AWC (mm/m)	Notes
Coarse sand	20–25	50–80	Frequent light irrigation required
Fine sand	12–18	80–120	Apply 10–15 mm per irrigation
Sandy loam	8–12	120–150	Good vegetable soil if managed
Silt loam	5–10	140–190	Ideal for borscht vegetables
Clay loam	3–8	160–220	Risk of waterlogging; deep wetting hard
Clay	1–4	190–260	Long intervals; avoid for sensitive crops

4.2 Field Capacity, Wilting Point, and Available Water

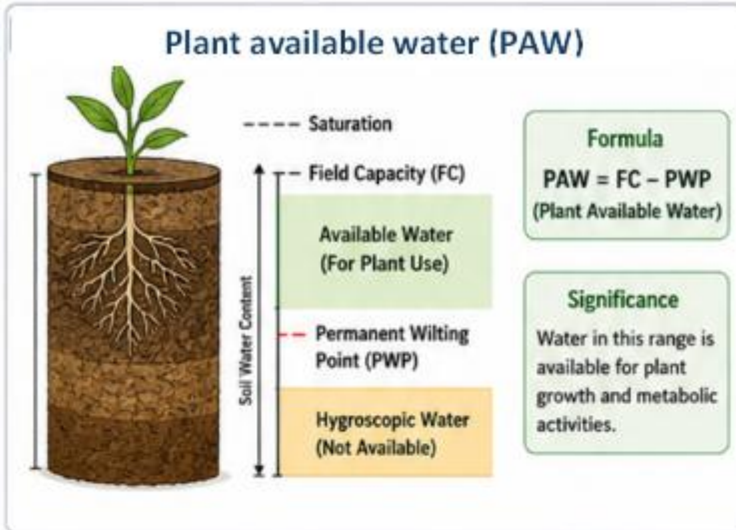

Figure 2 - Plant available water (PAW)

After a soil has been thoroughly wetted, gravity drains the largest pores within hours (in sandy soils) to days (in clay soils). The water content at which gravity drainage effectively stops is called field capacity (FC). The water content at which the crop can no longer extract water and wilts permanently is called the permanent wilting point (PWP). The difference between the two is the plant-available water (PAW).

Total available water (TAW) in the root zone is calculated by multiplying PAW by the effective rooting depth. For a cabbage crop on silt-loam with PAW = 16 % volume and a 50-cm root zone, TAW = 0.16 × 500 mm = 80 mm. Of this, only the readily available fraction (typically 40–55 %) should be allowed to deplete before irrigation; for a depletion factor p = 0.5, the readily available water (RAW) is 40 mm – the maximum acceptable depletion between two irrigations.

Tabel 11 – Field capacity, wilting point, and available water by texture (FAO-56).

Texture	**FC (% vol)**	**PWP (% vol)**	**PAW (% vol)**	**PAW (mm/m)**
Sand	10	4	6	60
Loamy sand	14	6	8	80
Sandy loam	18	8	10	100
Loam	26	10	16	160
Silt loam	31	13	18	180
Clay loam	38	18	20	200
Clay	42	22	20	200

Worked example: *Onion grown on a sandy loam (PAW = 100 mm/m) has an effective rooting depth of 30 cm; therefore TAW = 30 mm. The recommended depletion (p) for shallow-rooted vegetables is 0.30, so RAW = 9 mm. The crop must be irrigated when the cumulative ETc since the last irrigation reaches about 9 mm – which, at a peak ETc of 5 mm/day, means every second day.*

4.3 Soil Depth, Compaction, and Drainage

A deep, uncompacted soil is the cheapest possible irrigation investment. The Polish-Ukrainian comparison of Kherson and Kujawsko-Pomorskie noted that even with the same nominal rainfall, soil characteristics determine the productivity ceiling: chernozems with deep humus horizons hold three times the plant-available water of sandy podzols and therefore need three times fewer irrigation events for the same crop.

Tillage operations create compaction pans at the depth of the cultivation tool – typically 25–30 cm in cabbage and beet fields cultivated with a moldboard plough, or 15–20 cm in rotary-cultivated onion beds. A compaction pan reduces effective rooting depth, increases runoff, and forces the crop to depend on shallow irrigation. Deep ripping every 3–5 years restores rooting depth, especially on clay-loam soils.

Tabel 12 – Effect of compaction on effective rooting depth.

Crop	**Loss of root depth (cm)**	**Yield reduction**
Onion	5–10	5–15 %
Cabbage	10–15	15–25 %
Red beet	15–25	20–35 %
Carrot	20–30	30–50 % (forked roots, splitting)

Drainage is the often-forgotten side of irrigation management. Borscht vegetables tolerate waterlogged soil for only 2–5 days before root death and disease incidence rise. Surface drainage should be assured by minimal field slope (0.1–0.3 %) and by maintaining drainage furrows free of vegetation. On heavy clay loams, subsurface tile drainage may be necessary.

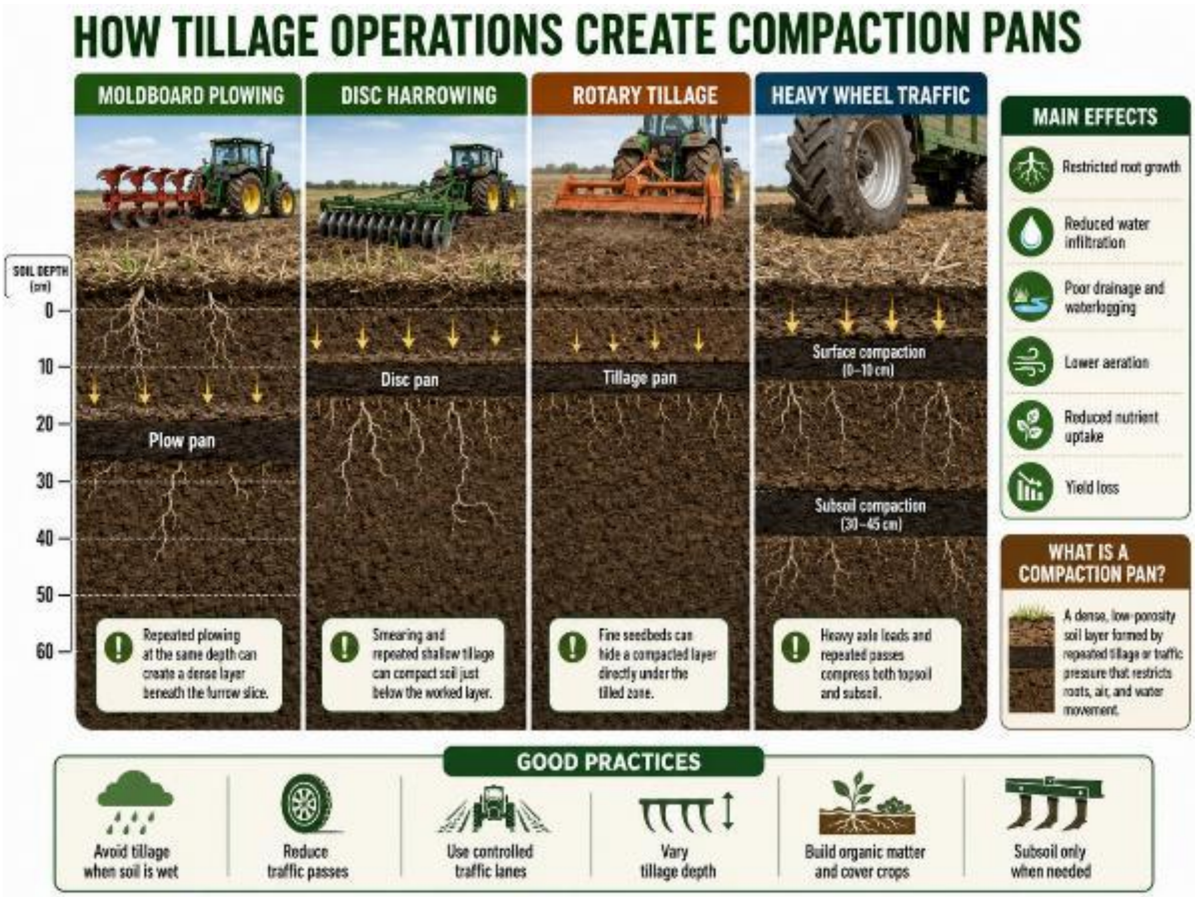

Figure 3 - How Tillage operations create compaction pans.

4.4 Topography and Microclimate

Within a single farm, microclimate variations are often as large as differences between agroclimatic zones. North-facing slopes are cooler and moister; south-facing slopes are warmer, drier, and accumulate more Etc (*explained in chapter 5*) . Shelterbelts (commonly composed of black locust, ash, or poplar in Ukrainian Steppe farms) reduce ETo (*explained in chapter 5*) by 10–20 % in the protected zone for a distance up to 10–15 times the height of the trees.

On level fields with very uniform soil, a single irrigation zone may serve the whole area. On rolling fields and on fields with mixed sandy and silty patches – typical of many areas of Kherson Oblast – the field should be divided into 2–4 irrigation zones, each scheduled separately. The cost of this subdivision is small (extra valves and submains), but the water and yield benefit can be 15–25 %.

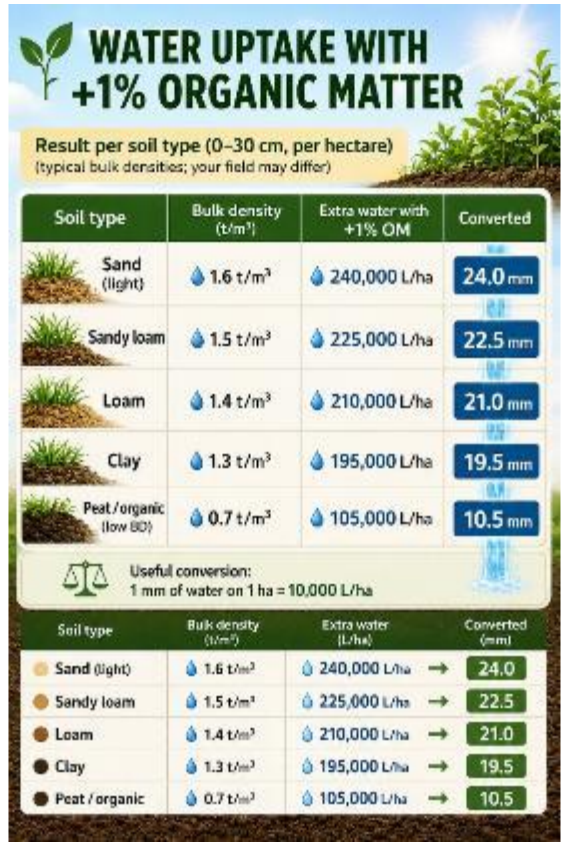

Figure 4 - water uptake of organic matter

Tabel 13 – Microclimate factors and how they modify irrigation need.

Factor	Direction of effect on ETc	Practical response
South-facing slope	+10 to +20 %	Higher irrigation depth; consider mulch
North-facing slope	−5 to −15 %	Reduced demand; watch for disease
Shelterbelt protection	−10 to −20 %	Reduce irrigation in lee zone
Frost pocket / hollow	Cool, longer dew	Late-season disease risk; reduce wetting
Exposed open field	+10 to +20 %	Add windbreak or use sub-canopy irrigation

4.5 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.

4.6 Water Quality and Salinity

Irrigation water in southern Ukraine commonly originates from the Dnipro, Inhulets, or Southern Bug rivers, from groundwater wells, or from on-farm reservoirs. Each source has its own salt and sediment profile. The Kakhovka system has shown that even predominantly fresh river water can become marginal during low-flow summers, with electrical conductivity (EC) rising from 0.4 to 1.2 dS/m. Long-term monitoring is therefore essential.

Tabel 14 – Salinity tolerance of vegetables (yield decline begins at).

Crop	Threshold ECe (dS/m)	50 % loss at (dS/m)	Tolerance class
Onion	1.2	4.3	Sensitive
Carrot	1.0	4.6	Sensitive
Cabbage	1.8	7.0	Moderately sensitive
Red beet	4.0	11.5	Moderately tolerant

The Ukrainian state standard DSTU 2730:2015 (Quality of natural water for irrigation. Agronomic criteria) defines four water-quality classes for agricultural use and is the binding reference for irrigation-water assessment in Ukraine.

5. Climatic and Environmental Factors

Climate is the single largest driver of vegetable water demand. Two crops grown on identical soils, with identical irrigation equipment, can require very different volumes of water in two different seasons – or in two different agroclimatic zones of Ukraine – simply because of differences in solar radiation, air temperature, vapour pressure deficit, wind speed, and the timing and amount of rainfall. This chapter introduces the climatic concepts that underpin all rational irrigation scheduling.

5.1 Reference Evapotranspiration (ETo) Concepts

Reference evapotranspiration, ETo, is the rate at which water would be lost from a hypothetical, well-watered, 0.12-m tall cool-season grass surface, expressed in mm per day. It depends only on weather variables – not on the crop or the soil – which is what makes it a useful reference for irrigation planning.

The FAO Penman–Monteith equation (FAO-56) is the international standard for computing ETo from daily air temperature, humidity, wind speed, and solar radiation. Where full meteorological data are not available, simpler methods such as Hargreaves (which uses only minimum and maximum temperature and extraterrestrial radiation) provide a workable substitute.

Tabel 15 – Typical daily ETo values for southern Ukrainian conditions by month.

Month	Tmax (°C)	Tmin (°C)	RHmean (%)	Wind (m/s)	ETo (mm/day)	Monthly ETo (mm)
April	14	5	65	3.2	2.5	75
May	21	10	60	3.0	4.0	124
June	26	14	60	2.8	5.2	156
July	29	16	55	2.7	6.0	186
August	28	15	55	2.5	5.4	167
September	22	10	60	2.6	3.5	105
October	14	5	70	2.8	1.8	56

Source: derived from Kherson region climatic averages; values are indicative and should be replaced by local meteorological data where available.

5.2 Rainfall Patterns and Effective Precipitation

Annual precipitation in Ukrainian vegetable-growing regions varies from roughly 700 mm in the western Forest zone to 350–450 mm in the southern Steppe (Kherson, Mykolaiv, Odesa, Zaporizhzhia oblasts). The growing-season fraction (April–September) is typically 55–65 % of annual rainfall.

Not all rainfall is available to the crop. Effective precipitation – the share that infiltrates and is stored in the root zone – is reduced by surface runoff, drainage below the root zone, and re-evaporation of intercepted water. For irrigation planning in southern Ukraine, an effective fraction of 0.7–0.8 is commonly used for events of 10–25 mm; very small events (<5 mm) and very large events (>40 mm in one day) should be assumed to contribute little or nothing to the rooting zone.

Tabel 16 – Long-term mean monthly rainfall for representative Ukrainian vegetable zones.

Zone (example oblast)	**Apr (mm)**	**May (mm)**	**Jun (mm)**	**Jul (mm)**	**Aug (mm)**	**Sep (mm)**
Polissia / Forest (Volyn)	40	55	75	90	65	55
Forest-Steppe (Kyiv)	35	50	65	70	55	45
North Steppe (Dnipro)	30	40	55	50	40	35
South Steppe (Kherson)	25	35	45	35	30	25
Black Sea coastal (Odesa)	28	32	40	30	25	30

Source: long-term Ukrhydromet averages; irrigation deficit = ETc − effective rainfall.

5.3 Temperature, Humidity, Wind and their Effects on Crops

Temperature governs the speed of crop development through accumulated growing-degree-days (GDD) and also affects transpiration through its strong influence on the saturation vapour pressure of air. Each vegetables has a base temperature below which development effectively stops (around 4 °C for onion, carrot, and cabbage; 5 °C for beet) and a thermal optimum (18–24 °C) above which heat stress begins to depress yield and quality.

Air humidity, expressed as relative humidity or, more usefully for irrigation, as vapour pressure deficit (VPD), determines how aggressively the atmosphere pulls water out of leaves. In the dry, often windy steppe afternoons of southern Ukraine, VPD can exceed 3.5 kPa, doubling transpiration relative to a humid morning at the same air temperature.

Wind compounds the demand by replacing the humid boundary layer around each leaf with drier ambient air. Windbreaks of poplar, willow, or maize strips reduce wind speed in the lee by 30–50 % for a distance of 10 H (ten times the windbreak height) and can lower seasonal ET by 5–15 %, with the largest savings on the dry days when irrigation is most expensive.

Table 7 – Climatic optima and stress thresholds.

Crop	Tbase (°C)	Topt day (°C)	Topt night (°C)	Tmax tolerated (°C)	Notes
Onion (bulb)	4	20–24	10–15	32	Bulb initiation triggered by daylength + temperature; heat at bulbing reduces size
Carrot	4	18–22	12–16	30	High temperatures cause poor colour and forked roots
Red beet	5	18–22	10–14	30	Heat + drought = zoning (white rings) in roots
White cabbage	4	16–22	10–14	28	Heat during head formation causes loose, cracked heads

Source: compiled from FAO crop ecology guidelines and regional Ukrainian agronomic recommendations.

6. Irrigation Systems: Types and Suitability

The choice of irrigation system determines water-use efficiency, energy cost, labour requirements, the suitability of the operation for fertigation, and ultimately the marketable yield per cubic metre of water applied. This chapter describes the systems in regular use on Ukrainian vegetable farms and provides selection criteria for crops.

6.1 Surface Irrigation (Furrow, Border, Basin)

Figure 5 - Furrow Irrigation. Picture: Andrii Yalnaskyi

Surface irrigation moves water across the field by gravity. Furrow irrigation – the dominant surface method in Ukrainian vegetable fields equipped from the Kakhovka and other systems – delivers water through small channels between crop rows. Capital cost is low, but field application efficiency rarely exceeds 50–60 %; the rest is lost to deep percolation at the head end and runoff at the tail end. Furrow irrigation is poorly suited to fertigation because nutrient distribution along the run is uneven and a large fraction of soluble nitrogen leaches below the root zone.

6.2 Sprinkler Systems (Solid-Set, Hose-Reel, Center Pivot)

Sprinkler systems spray pressurised water through the air, simulating rainfall. They are versatile, work on uneven terrain, cool the crop on hot days, and can also be used for frost protection. Application efficiency is typically 70–80 % under calm conditions but drops to 50–60 % under wind speeds above 4 m/s, which are common in the southern Steppe.

Hose-reel travellers and centre-pivots dominate Ukrainian field-scale sprinkler equipment. Centre-pivots irrigate large circular blocks (40–130 ha) with low labour, but require uniform, square-or-near-square fields. Hose-reels are flexible and inexpensive but labour-intensive. Solid-set systems with overhead micro-sprinklers are common in nurseries and small protected plots.

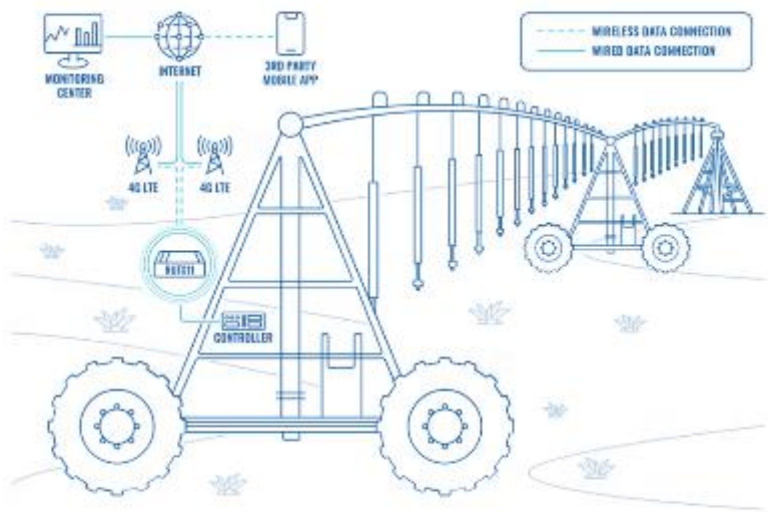

Figure 6 - Pivot. By Teltonika.

6.3 Drip Irrigation (Surface and Subsurface)

Drip irrigation delivers water at low pressure (0.5–2.0 bar) directly to the root zone through emitters spaced along laterals laid on the soil surface or buried (subsurface drip irrigation, SDI). Field application efficiency reaches 90–95 % under good management. Drip is uniquely suited to fertigation: nutrient distribution is determined by emitter discharge uniformity, which in modern pressure-compensating systems is better than 95 %.

Figure 7 - Drip irrigation. By Life Aclima.

Surface drip with disposable single-season tape is the dominant choice for direct-seeded carrot, beet, and onion in Ukraine; multi-season drip line (1.0–1.2 mm wall thickness, 6–10 year life) is used on transplanted cabbage and onion on more permanent vegetable blocks. SDI is increasingly common where rodent and UV damage to surface laterals is a recurring problem.

6.4 Wetting Pattern and System Choice

The wetting pattern of a drip emitter under field conditions is a function of soil texture, emitter discharge, and the duration and frequency of irrigation. On sandy soils, the wetting bulb tends to be narrow and deep (high vertical-to-lateral ratio); on clay loams it spreads laterally and is shallower. For widely spaced cabbage planted at 0.5 × 0.6 m, an emitter spacing of 0.4–0.6 m gives good overlap; for narrow-row carrot and beet, 0.2–0.3 m spacing with a single drip line per twin-row bed is the standard. Onion, with its dense plant spacing and shallow root, demands the closest emitter spacing of all (0.15–0.25 m).

6.5 Protected Cultivation Irrigation (Greenhouse, Tunnel)

In greenhouses and high tunnels, drip irrigation combined with fertigation is the standard. Substrate-grown (peat bag, coco-coir, rockwool) production for transplant nurseries and high-value salad crops uses fine drip with 1 L/h drippers and individual stake-pegs at each plant. Recirculating soilless systems (NFT, ebb-and-flow) are used for microgreens and bunching onion. Daily irrigation under protection is typically 1.2–1.5 × open-field ETc during the warmest months because of higher day temperatures.

6.6 Selection Criteria for Vegetable Crops

The choice between surface, sprinkler, and drip is rarely binary. Many Ukrainian operations run hybrid systems: sprinkler establishment of direct-seeded onion until the third true leaf, followed by drip thereafter; or sprinkler-only for cabbage on level land where drip would be damaged by mechanised harvest. Selection criteria include water quality and quantity, soil texture, field shape, energy availability, available labour, and the value of the crop. The summary below shows the suitability of each system for Ukrainian vegetable production.

Table 8 – Suitability of major irrigation systems in Ukrainian conditions.

Criterion	**Furrow**	**Sprinkler (centre pivot)**	**Drip (surface)**	**SDI**
Application efficiency (%)	50–60	70–80 (calm)	90–95	90–95
Wind sensitivity	Low	High (>4 m/s)	None	None
Suitability for fertigation	Poor	Moderate	Excellent	Excellent

6. Irrigation Systems: Types and Suitability

Criterion	Furrow	Sprinkler (centre pivot)	Drip (surface)	SDI
Capital cost (€/ha)	500–1 500	2 500–4 000	6 000–10 000	8 000–12 000
Labour requirement	High	Low	Moderate	Low
Best fit crops	Cabbage on flat land	Cabbage; cool-day onion	Onion, carrot, beet	Cabbage on perennial blocks

7. Irrigation Scheduling

Irrigation scheduling answers two questions: when to irrigate, and how much water to apply. Three familiar approaches are in routine use in Ukrainian vegetable production: soil-moisture-based (tensiometers and electronic sensors), plant-based (visual observation, canopy temperature), and ETc-based (daily water balance from weather data). The most reliable schedules combine elements of all three.

7.1 Soil Moisture-Based Scheduling

Tensiometers measure soil matric potential (the suction with which water is held by the soil) in centibars (cb) or kilopascals (kPa). For the borscht vegetables on medium-textured soils, irrigation is typically triggered when tensiometer readings at 30 cm depth reach 30–40 cb (onion: 20–25 cb; carrot, beet, cabbage: 30–40 cb). Tensiometers are inexpensive, robust, and locally interpretable, but they require daily checking and refilling and stop reading reliably above about 80 cb.

Capacitance and frequency-domain reflectometry (FDR) sensors measure volumetric water content directly and continuously; modern wireless models report to a smartphone every 15 minutes. Time-domain reflectometry (TDR) probes give even higher accuracy and are the reference instrument for research, but cost more. For an operating farm, two tensiometers per management zone (one at 15 cm, one at 30 cm) provide adequate scheduling information at a tenth of the price of an electronic system.

Table 9 – Tensiometer trigger values for irrigation on medium-textured soils.

Crop	Sensor depth (cm)	Trigger (cb)	Refill target (cb)	Comment
Onion (bulbing)	15	20	5–8	Shallow, sparse roots; never let it dry
Carrot	30	35	10	Tolerates slight drying after canopy closure
Red beet	30	40	10	Most drought-tolerant of the four; do not over-irrigate

Crop	Sensor depth (cm)	Trigger (cb)	Refill target (cb)	Comment
White cabbage (head formation)	30	30	10	Avoid both stress and waterlogging

7.2 Plant-Based Indicators

Crops themselves give early warnings of water stress that an experienced grower learns to read. Slight darkening of foliage colour, loss of leaf turgor in the late afternoon (with rapid recovery overnight), and partial closure of stomata visible as a duller leaf surface are early signs. Permanent wilting, leaf rolling, and silvering of cabbage outer leaves indicate severe stress that has already cost yield. Infrared canopy thermometers, which measure leaf temperature relative to air temperature, are a quantitative version of the same approach: a canopy more than 2–3 °C warmer than air on a cloudless day signals stomatal closure and the need to irrigate.

7.3 ETc-Based and Water-Budget Scheduling

In this approach, daily water demand is calculated as **ETc = Kc × ETo**, where ETo is reference evapotranspiration (Section 5.1) and Kc is the crop coefficient (Sections 2.3, 3, 8). A simple daily soil-water balance is then maintained: *SWD(today) = SWD(yesterday) + ETc − effective rainfall − irrigation*, where SWD is the soil water deficit, in mm, relative to field capacity. Irrigation is scheduled when SWD reaches the allowable depletion (typically 0.30–0.50 of total available water, depending on crop and stage).

Table 10 – Worked weekly water-budget example for onion (bulbing stage; allowable depletion ~25 % of TAW).

Day	ETo (mm)	Kc	ETc (mm)	Rain (mm)	Irrig. (mm)	Cumulative SWD (mm)
Mon	6.1	1.05	6.4	0	0	6.4
Tue	6.4	1.05	6.7	0	0	13.1
Wed	5.8	1.05	6.1	0	12	7.2
Thu	6.2	1.05	6.5	5	0	8.7
Fri	6.0	1.05	6.3	0	0	15.0

Day	ETo (mm)	Kc	ETc (mm)	Rain (mm)	Irrig. (mm)	Cumulative SWD (mm)
Sat	5.5	1.05	5.8	0	12	8.8
Sun	5.0	1.05	5.3	0	0	14.1

Irrigation triggered when SWD ≥ 12 mm. Onion silt-loam, bulbing stage.

7.4 Decision-Support Tools and Apps

Several free or low-cost decision-support tools combine weather forecasts, crop coefficients, and user inputs (planting date, soil type, irrigation system) to recommend irrigation timing. Examples available in Ukrainian interfaces include FAO AquaCrop, CropWat, and several proprietary tools (Netafim NetBeat, Naandanjain DripWise). On-farm trials in Kherson and Odesa oblasts have shown that ETc-based scheduling combined with one tensiometer per block reduces seasonal water use by 15–30 % relative to fixed-interval irrigation, with no yield penalty.

7.5 Deficit Irrigation Strategies for Water-Scarce Conditions

When water is limiting, regulated deficit irrigation (RDI) applies less than full ETc at growth stages where the crop is relatively insensitive to stress. For carrot and red beet, the early canopy expansion phase (days 25–45 after sowing) is comparatively tolerant of mild stress; for cabbage, the period between transplanting and rosette closure can be deficit-irrigated with little penalty. None of the four borscht vegetables tolerates deficit irrigation during their critical stage (bulbing for onion, root thickening for carrot/beet, head formation for cabbage).

8. Water Requirements by Growth Stage and Cropping System

This chapter draws together the ETc curves, system efficiencies, and scheduling principles of Chapters 2–7 into ready-to-use seasonal water budgets for each of the four borscht vegetables under the cropping systems commonly used in Ukraine.

8.1 Transplanted vs. Direct-Seeded Operations

Cabbage in Ukraine is almost exclusively transplanted (40-day-old plants set out at 50 × 60 cm in late April for early-summer harvest or in mid-June for autumn storage). Onion is grown both from sets (most common for early sweet onion) and from seed (storage varieties); transplanted onion from seedling trays is increasing in commercial drip-irrigated systems. Carrot and red beet are direct-seeded, often in twin-row beds 1.4 m wide carrying two drip lines.

Transplanted crops require a short, intense irrigation burst immediately after planting (8–12 mm/day for 3–5 days) to establish the root system in fresh soil. Direct-seeded crops need light, frequent surface irrigation (4–6 mm/day, twice daily on hot days) until emergence, after which intervals can be lengthened as roots grow downward.

8.2 Open-Field Production

The following table summarises seasonal water budgets for fully irrigated open-field production of each borscht vegetable on medium soil in the southern Steppe (Kherson conditions, May–September). Values for the Forest-Steppe are typically 20–30 % lower because of higher effective rainfall.

Table 11 -– Indicative seasonal water budgets for vegetables under drip irrigation, southern Ukraine.

Crop	Season (days)	ETc total (mm)	Eff. rain (mm)	Irrig. need (mm)	Irrig. (m^3/ha)	Target yield (t/ha)
Onion (storage)	120–140	550–650	150	400–500	4 000–5 000	45–65
Carrot (long-season)	120–150	450–550	180	270–370	2 700–3 700	55–80
Red beet	100–120	400–500	160	240–340	2 400–3 400	40–60
White cabbage (storage)	100–130	450–550	170	280–380	2 800–3 800	70–100

Source: synthesised from Kebede et al. (2025) for onion ETc; Rolbiecki et al. (2017–2019) for carrot and red beet; Singh et al. (2014) for cabbage; FAO-56 for Kc.

8.3 Protected and Hydroponic Production

Protected cultivation (high tunnels, unheated and heated greenhouses) for early-season cabbage transplant production and high-value salad beet is expanding in central and western Ukraine. Daily irrigation under protection is typically 1.2–1.5 × open-field ETc during the warmest months because of higher day temperatures, although total seasonal water use is similar because the growing season is shorter.

Soilless (hydroponic) production of red beet leaves (microgreens) and onion bunching is a small but growing segment. Recirculating nutrient-film and ebb-and-flow systems achieve 20–30 L of water per kg of marketable produce, against 60–120 L/kg in well-managed open-field drip.

8.4 Crop Rotation and Multiple Cropping

A four-year rotation alternating one of the borscht vegetables with a winter cereal (wheat or barley) and a legume (pea or soybean) is the recommended baseline for irrigated Ukrainian vegetable land. Rotation reduces soil-borne disease, balances nutrient demand, and spreads irrigation peak demand across the calendar. On drip-equipped fields, the same buried sub-main and filter station can serve the vegetable course and a subsequent cereal crop with only the laterals being moved or replaced.

Table 12 – Yield response to irrigation level (% of full irrigation yield).

Crop / irrigation level	100 % ETc	80 % ETc	60 % ETc	40 % ETc	Rainfed
Onion (storage)	100	92	75	55	35
Carrot	100	95	80	60	45
Red beet	100	97	85	65	55
White cabbage	100	94	78	58	40

Relative yield (%) compared with fully irrigated treatment (100). Compiled from peer-reviewed trials in Poland, Ethiopia, India, and Ukraine.

Table 13 – Critical growth stage and minimum soil-moisture target.

Crop	**Critical stage**	**Duration (d)**	**Soil moisture target (% TAW)**	**Consequence of stress**
Onion	Bulb initiation to maturity	40–60	≥ 80 %	Small bulbs, doubles, premature bolting
Carrot	Root thickening	30–50	≥ 65 %	Forked or splitting roots, low sugar
Red beet	Root enlargement	30–45	≥ 65 %	Zoning (white rings), low Brix
White cabbage	Head formation	25–40	≥ 70 %	Loose heads, cracking, low weight

TAW = total available water in the root zone. Source: FAO-56, supplemented by regional trial data.

9. Fertigation

Fertigation – the injection of soluble fertilizers into the irrigation stream – is the operational technique that, more than any other, justifies the investment in pressurised irrigation. By delivering nutrients with the water, in small daily doses, precisely where the active roots are, fertigation can raise fertilizer-use efficiency from the 30–50 % typical of broadcast application to 80–90 %. Reported field results include 20–30 % reductions in total fertilizer use, 30 % gains in nitrogen-use efficiency, and substantial decreases in nitrate leaching to groundwater. Chemigation is the same technique applied to non-fertilizer chemicals (acids for cleaning, sometimes chlorine for line maintenance, and – under strict regulation – some pesticides). This chapter covers the principles, equipment, and operational rules.

9.1 Principles of Fertigation

Three fundamental concepts underpin all fertigation: solubility, compatibility, and timing. Only fully water-soluble fertilizers should be used; insoluble residues block emitters and damage pumps. Not all soluble fertilizers can be mixed in the same tank: calcium salts will precipitate with phosphates and sulphates, and chelated micronutrients are sensitive to pH. Timing is the central agronomic advantage: instead of broadcasting all the nitrogen at planting, the grower delivers small daily doses matched to the actual uptake curve of the crop, supplying nutrients exactly when the plant needs them.

The two most important nutrients to fertigate are nitrogen (extremely mobile in soil; high risk of leaching when broadcast and irrigated) and potassium (taken up in large amounts during root and bulb thickening). Phosphate is much less commonly fertigated because of precipitation risks and because P is relatively immobile and well managed by pre-plant placement.

9.2 Injection Equipment

Three families of injectors are in routine use on Ukrainian vegetable farms, each with its own niche:

- Venturi injectors are simple, inexpensive (~€100–€300), driven by the pressure difference they themselves create in a constriction in the main line. They have no moving parts, but they require a 20–30 % pressure drop across the device and their injection rate varies with system pressure. Best for small operations and constant-pressure systems.
- Piston- and diaphragm-driven dosing pumps (electric or hydraulic) deliver a precisely metered volume per unit time regardless of system pressure. Capital cost is higher (~€600–€2 500), but the precision is essential for proportional fertigation in large operations or for chemigation requiring exact dose.

- By-pass tanks (fertilizer tanks plumbed in parallel with the main line) are the simplest of all – a small pressure drop diverts a fraction of the flow through the tank, dissolving and entraining fertilizer. The injection rate is uneven (high at first, declining as the tank is depleted), so by-pass tanks are best used for non-time-critical micronutrient or acid additions, not for precise N or K dosing.

Table 9.1 – *Comparison of fertigation injection equipment.*

Injector	Cost (€)	Precision	Pressure loss (%)	Maintenance	Best fit
Venturi	100–300	Moderate	20–30	Low	Small to medium drip blocks; constant-pressure systems
Diaphragm pump (hydraulic)	600–1 500	High	0–5	Moderate	Medium to large blocks; proportional fertigation
Piston pump (electric)	1 000–2 500	Very high	0–5	Moderate	Greenhouses; very precise dosing; chemigation
By-pass tank	150–400	Low	5–10	Very low	Acid flushes; micronutrient supplements; small farms

9.3 Nutrient Requirements and Scheduling Vegetables

Each crop has a characteristic nutrient uptake curve – the rate at which it takes up nitrogen, phosphorus, potassium, and the secondary nutrients changes with growth stage. Fertigation matches the daily dose to this curve. The tables below summarise typical seasonal N–P–K removal and recommend a daily-fertigation distribution across the main phenological stages.

Table 14 – Total seasonal fertiliser uptake (kg/ha at target yield).

Crop	Target yield (t/ha)	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	N : P : K ratio
Onion	55	140	60	180	1.0 : 0.43 : 1.29
Carrot	70	150	70	300	1.0 : 0.47 : 2.00

Crop	Target yield (t/ha)	N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	N : P : K ratio
Red beet	50	160	60	280	1.0 : 0.38 : 1.75
White cabbage	85	260	100	320	1.0 : 0.38 : 1.23

Removal in harvested product. Applied rates may be 10–20 % higher early in a rotation and 10–20 % lower after a high-N preceding crop (e.g. legume, manure).

Table 15 – Indicative fertigation schedule (% of total seasonal N) for storage onion under drip.

Growth stage	Days from emergence	% of total N	kg N/ha	Fertigation freq.	N source
Establishment	0–25	10 %	14	2× per week	Calcium nitrate
Vegetative growth	25–60	30 %	42	3× per week	Ammonium nitrate + KNO_3
Bulb initiation	60–85	35 %	49	Daily	Urea + KNO_3
Bulb fill	85–115	20 %	28	Daily, declining	KNO_3 (low N)
Maturation	115–130	5 %	7	2× per week	K_2SO_4 (no N)

9.4 Chemigation – Beyond Fertilizer

Chemigation broadens fertigation to non-fertilizer chemicals delivered through the irrigation system. Three categories matter on a vegetable farm. Chlorination – usually as sodium hypochlorite delivered to maintain 1–2 mg/L free chlorine continuously during irrigation – prevents biological clogging. Acid injection (phosphoric, nitric, or sulphuric acid down to pH 5.5–6.5) keeps calcium and iron in solution and reduces precipitation in emitters. Pesticide application through irrigation is permitted only for a limited list of products and is regulated under Ukrainian Ministry of Health rules; it requires a back-flow preventer, double-check valves, and trained operators.

10. System Design and Installation

Sound hydraulic design is the foundation of every successful drip-fertigation system. A system that delivers the correct flow at the correct pressure to every emitter, year after year, repays its design cost many times over. This chapter outlines the design steps and the most common errors to avoid.

10.1 Hydraulic Principles: Flow, Pressure, Pressure Loss

Pressurised irrigation systems obey two physical laws. The continuity equation requires that flow be conserved through the system: what leaves the pump must equal the sum of what each emitter discharges. The energy equation requires that the head supplied by the pump be balanced by friction losses along the pipes plus the working pressure at each emitter. Friction loss rises with the square of velocity, so doubling pipe diameter cuts friction loss by roughly a factor of 30; oversizing pipes by one diameter step is the cheapest investment a designer can make. Pressure-compensating emitters maintain constant flow over a wide pressure range (typically 0.5–4 bar) and are the standard choice on undulating ground or on long laterals.

10.2 Pump, Filtration, and Pressure Regulation

The pump must supply the system flow at the design pressure with a safety margin of 10–15 %. Centrifugal pumps driven by 7.5–22 kW electric motors cover the typical Ukrainian vegetable-farm size range (1–20 ha). Filtration is non-negotiable: even canal water that "looks clean" carries enough particulate to clog drip emitters within a few weeks. Two-stage filtration – primary sand filter (or hydro-cyclone for sand-laden borehole water), followed by 120-mesh disc filter as final guard – is the Ukrainian best-practice standard. Pressure regulators or pressure-compensating emitters smooth out the variations that arise from elevation changes and lateral friction loss.

Table 16 – Filtration requirements by irrigation system and water source.

System / water source	Primary filter	Final filter (mesh)	Comment
Drip / clean borehole	Hydrocyclone	120 mesh disc	Add small sand filter if Fe > 0.2 mg/L
Drip / surface canal	Sand media	120 mesh disc	Chlorinate continuously 1–2 mg/L
Drip / on-farm pond	Sand media	120–150 mesh disc	Algae growth – shock chlorinate monthly

System / water source	Primary filter	Final filter (mesh)	Comment
Sprinkler / any source	Screen 50 mesh	—	Lower filtration demand than drip
Subsurface drip (SDI)	Sand media	155 mesh disc	Plus pressure-compensating emitters

10.3 Pipe Layout and Emitter Spacing

Mainlines and sub-mainlines are typically buried (60–80 cm depth) and made of PVC or PE. Drip laterals are above-ground (surface drip) or 15–35 cm below the surface (SDI). For carrot and beet sown in twin-row beds 1.4 m wide, one lateral per bed with 30 cm emitter spacing and 2 L/h emitters gives an instantaneous application rate of 4.8 mm/h. For cabbage at 0.6 m × 0.5 m, one lateral per row with 0.5 m emitter spacing and 2 L/h emitters delivers 2.4 mm/h. For onion planted in twin or quadruple rows on 1.2 m beds, two laterals per bed with 0.2–0.3 m emitter spacing are appropriate.

Table 17 – Recommended drip layouts for vegetables.

Crop	Bed / row spacing	Lateral per bed	Emitter spacing (m)	Emitter rate (L/h)	Notes
Onion (twin row)	1.2 m bed, 2 rows	2	0.20–0.30	1.0–2.0	Shallow-rooted; closer spacing
Onion (4-row)	1.4 m bed, 4 rows	2	0.20	1.0	Pressure-compensating emitters recommended
Carrot	1.4 m bed, twin rows	1 (centre)	0.30	1.6–2.0	Lateral mid-bed; SDI at 15 cm common
Red beet	1.4 m bed, twin rows	1 (centre)	0.30	1.6–2.0	Same layout as carrot
White cabbage	0.6 × 0.5 m	1 per row	0.50	2.0	Lateral alongside the row

10.4 Installation Procedures and Quality Control

Installation follows a standard sequence: survey and design verification on the field; trench excavation for main and sub-mainlines; pump station construction (concrete pad, filter manifold, pressure gauges, isolation valves, drain and air-vent); lateral layout; first flushing and pressure test (at 1.5 × operating pressure for 30 min) before the field is cropped.

Each operator should keep a system as-built drawing, a hydraulic record (flow vs. pressure at design points), and an emitter discharge audit (measured discharge of 16 randomly chosen emitters along each lateral) from commissioning. These three documents are the baseline against which seasonal maintenance is judged.

11. Operation and Maintenance

Routine operation and maintenance determine whether an irrigation system reaches its 12–15 year design life or fails in season three. Three groups of failures dominate field experience: emitter clogging (physical, biological, or chemical), filter neglect, and pump-station problems. This chapter provides operating procedures that prevent these failures.

11.1 Routine Daily and Weekly Checks

Table 18 – Routine inspection schedule for a drip-fertigated vegetable system.

Frequency	Item	What to check	Action / target
Daily	System pressure at filter inlet/outlet	Difference between inlet and outlet pressure	Backflush when ΔP > 0.4 bar
Daily	Fertilizer tank level + pH/EC	Visual + handheld EC/pH meter	Refill; adjust pH 5.5–6.5
Daily	Visual: dry spots in field	Walk one block per day	Mark and investigate same day
Weekly	Emitter discharge audit	16 random emitters along each lateral	Replace lateral if CV > 15 %
Weekly	Pump station leaks, vibration	Listen and look at couplings, bearings	Tighten / grease / replace
Monthly	Sand-media filter inspection	Open and inspect media level	Top up sand; replace if caked
Monthly	Chlorine injection log	Verify injection rate	Maintain 1–2 mg/L continuous
Seasonally	End-of-season flush	Open all lateral ends, flush 5 min each	Plug ends with caps for off-season

11.2 Clogging Prevention and Treatment

Clogging arises from three causes – physical (particulates that escape the filter), biological (bacterial slimes and algal growth), and chemical (precipitation of iron, manganese, calcium carbonate). The first line of defence is correct filtration. The second is continuous low-level chlorination (1–2 mg/L of free chlorine, injected at the head of the system continuously during irrigation), which prevents biofilm growth. The third is periodic shock treatment: 30 mg/L chlorine for 30 minutes, or acid flushing with 0.6 % phosphoric or nitric acid down to pH 2 for 30 minutes, applied once mid-season and once at season's end. After any chemical treatment, the system must be flushed with clean water for at least one full main-line volume before normal operation resumes.

Table 19 – Common drip irrigation problems, causes, and corrective actions.

Symptom	Likely cause	Diagnostic test	Corrective action
Pressure rises at filter inlet	Filter clogging	ΔP gauge reading > 0.4 bar	Backflush or clean discs
Pressure drops in laterals	Mainline leak / failed pressure regulator	Walk line, check regulator	Repair leak; replace regulator
Low emitter discharge throughout	Biofilm / slime	Cut open emitter, inspect	Shock chlorination 30 mg/L 30 min
Low discharge end of lateral	Sediment + line too long	Open end cap and flush	Shorten lateral or use larger ID
White scale at emitter	$CaCO_3$ precipitation	Inspect; check water pH/hardness	Acid flush; pH down to 5.5–6.5
Red/brown stain at emitter	Iron oxidation	Water test for Fe > 0.2 mg/L	Aeration + sand filtration; chlorination
Drip line damaged / chewed	Rodents (SDI)	Visual inspection at low pressure	Rodent control; bait stations
Wet spots between emitters	Mechanical damage / aged tape	Walk and inspect	Splice or replace section

11.3 End-of-Season Procedures

At the end of each season, the system should be flushed thoroughly (open all lateral ends, run the pump for 5 minutes per lateral, close each end as the discharge runs clear), filters cleaned and stored dry, dosing pumps drained and cycled with clean water, and exposed risers and valves protected against freezing. Drip tape is generally collected and stored under cover; thick-walled drip line (1.0–1.2 mm wall, designed for 6–10 seasons) is left in place. Buried SDI laterals are flushed and pressurised to about 0.5 bar for over-winter to prevent root intrusion.

11.4 Troubleshooting Guide for Field Operators

Field operators should follow a simple diagnostic sequence whenever performance is suspect:

(1) check pressure gauges at the pump, after the filter, and at the lateral inlet;

(2) walk one block per day and look for dry spots, wet spots, and ponding;

(3) collect water samples from emitters at the beginning, middle, and end of three random laterals and time their discharge into a graduated cup;

(4) cross-check the result against the emitter rating and the previous audit. Investigations always proceed from upstream (pump) to downstream (emitter); this sequence isolates the cause of a problem in the smallest possible part of the system.

12. Sustainability and Climate-Smart Irrigation

Vegetable irrigation in Ukraine operates within tightening environmental, economic, and climatic constraints: rising energy prices, falling groundwater tables in some southern districts, more frequent summer heat waves, and stricter European water-quality standards. Climate-smart irrigation responds to these pressures by combining water-saving technology with soil-conservation practices, on-farm water capture, and a long-term view of the resource.

12.1 Water-Use Efficiency Metrics

Three water-use-efficiency metrics are in routine use and should be reported on every farm: irrigation water-use efficiency (IWUE = marketable yield / irrigation water applied, in kg/m³); evapotranspiration water-use efficiency (ETWUE = yield / ETc); and crop water productivity (WP = yield / total water consumed). For drip-fertigated borscht vegetables in southern Ukraine, achievable IWUE values are 12–18 kg/m³ for onion, 18–25 kg/m³ for carrot and beet, and 22–30 kg/m³ for cabbage. Furrow-irrigated comparators in the same district typically deliver less than half these values.

Table 20 – Water-use efficiency benchmarks for vegetable irrigation systems.

Crop	Irrigation system	Yield (t/ha)	Irrig. (mm)	IWUE (kg/m³)	Comment
Onion	Furrow	30–40	650	4.6–6.2	Baseline
Onion	Sprinkler	40–50	550	7.3–9.1	+ disease risk
Onion	Drip + fertigation	55–65	450	12.2–14.4	Best practice
Carrot	Furrow	40–55	500	8.0–11.0	Baseline
Carrot	Drip + fertigation	65–80	320	20.3–25.0	Best practice
Red beet	Furrow	30–45	450	6.7–10.0	Baseline
Red beet	Drip + fertigation	45–60	290	15.5–20.7	Best practice
White cabbage	Sprinkler	60–80	500	12.0–16.0	Baseline

Crop	Irrigation system	Yield (t/ha)	Irrig. (mm)	IWUE (kg/m³)	Comment
White cabbage	Drip + fertigation	85–100	350	24.3–28.6	Best practice

12.2 Mulching, Cover Crops, and Soil Water Conservation

Plastic mulch (typically black or biodegradable polyethylene, 25–30 µm thick) suppresses soil evaporation by 50–80 %, raises early-season soil temperature by 2–4 °C, and reduces weed competition. FAO-56 recommends multiplying mid-season Kc by 0.7–0.9 for plastic-mulched crops to account for the reduced evaporation; for fully mulched fertigated cabbage and onion, in-season water savings of 20–30 % are typical.

Cover crops grown in the fallow period (winter rye, vetch, mustard) protect the soil surface from wind and water erosion, scavenge residual nitrogen, and add organic matter that improves the water-holding capacity of sandy soils. Each 1 % increase in soil organic matter raises available water capacity by approximately 0.15 mm of water per cm of soil depth.

Figure 8 - Cover crop: mix Rye&Vetch, by Picasa

12.3 Rainwater Harvesting and On-Farm Storage

Figure 9 - Rainwater harvesting, by Invade Agro Global

On-farm storage ponds and tanks turn winter and spring rainfall into summer irrigation supply. A pond holding 4 000–6 000 m³ per irrigated hectare is sufficient to bridge a six-week drought on most southern Ukrainian vegetable rotations. Roof catchment from large packing sheds and machinery buildings, channelled to lined ponds, supplies high-quality, low-sediment water that is particularly suitable for drip irrigation of fresh-market produce.

12.4 Drainage and Salinity Management

Where irrigation water has electrical conductivity above 1.0 dS/m – common in the lower Dnipro and some borehole sources in Mykolaiv and Odesa oblasts – the leaching fraction (the share of applied water that drains below the root zone, carrying accumulated salts) must be carefully managed.

Drip irrigation with daily applications keeps the wetted bulb at low salinity even under marginal water; once or twice per season, an intentional over-irrigation (leaching event) flushes accumulated salts below the root zone. Sub-surface drainage is required where the water table rises into the root zone seasonally.

12.5 Climate Change Adaptation

Projections for 2030–2050 over southern Ukraine include 1.5–2.5 °C increases in summer mean temperature, 5–15 % reductions in growing-season rainfall, and a higher frequency of multi-day heat waves above 30 °C. Adaptation strategies for irrigated vegetable production include earlier or later planting dates to shift the critical stage out of peak heat, deployment of shade nets in nurseries and tunnels, increased reliance on drip and SDI (which are far less affected by wind and heat than sprinklers), and rotation toward more drought-tolerant cultivars (including the more heat-tolerant onion and beet varieties already grown in southern Europe).

13. Economic, Regulatory, and Policy Considerations

Investment in modern irrigation has to pay for itself within the planning horizon of the farm, generally 5–10 years. This chapter sets out the cost components, illustrates a representative cost-benefit analysis for converting from furrow to drip fertigation, summarises the Ukrainian regulatory framework, and notes the main donor and government support mechanisms available in 2025–2026.

13.1 Cost-Benefit Analysis of Irrigation Investment

A typical drip-fertigation installation for one hectare of borscht vegetables in southern Ukraine in 2025 had the following capital cost structure (figures from supplier quotations and recent ProAgro / FAO project documentation):

Table 21 – Indicative capital cost (€/ha) of drip-fertigation systems.

Component	Low (€)	Mid (€)	High (€)	Note
Pump + electric motor (15–22 kW)	1 500	2 200	3 000	Centrifugal, multi-stage
Sand + disc filter station	1 200	1 800	2 400	120 mesh final
Fertigation injectors + tanks	600	1 000	1 500	Diaphragm pump for medium farms
Mainline + sub-mains (PVC/PE)	1 200	1 800	2 400	Buried; 1 ha block
Drip laterals (single-season tape)	800	1 100	1 400	Replaced each year
Drip line (multi-season, 6-year)	1 800	2 400	3 000	Choose tape OR line, not both
Control valves + pressure regulators	300	500	700	Per block
Installation + commissioning	500	800	1 200	Labour + contractor

Component	Low (€)	Mid (€)	High (€)	Note
Total (tape system)	6 100	9 200	12 600	Annual replacement of laterals
Total (multi-season line)	7 100	10 500	14 200	6-year lateral life

Excludes water source (canal connection or borehole drilling) and field-side water storage.

Operating cost includes energy (typically 350–650 kWh/ha/season for drip), filter media renewal, replacement parts, labour for daily monitoring (around 30 hours per hectare per season), and the seasonal cost of drip tape if used. Against these costs, the typical revenue gains from converting one hectare of carrot or cabbage from furrow to drip-fertigation are 15–25 t/ha additional yield, 20–30 % fertilizer savings (€100–€200/ha), and a 30–50 % labour saving on irrigation supervision. Payback periods of 3–5 years are reported across recent project evaluations.

Table 22 – Simplified 5-year cost benefit summary for converting 1 ha from furrow to drip-fertigation.

Item (€/ha)	Year 0	Year 1	Year 2	Year 3	Year 4
Capital investment	−9 200	0	0	0	0
Lateral replacement (tape)	0	−1 100	−1 100	−1 100	−1 100
Energy + filter media	0	−450	−470	−490	−510
Extra yield revenue (vs furrow)	0	+3 800	+4 000	+4 200	+4 200
Fertilizer savings	0	+160	+170	+180	+180
Labour savings	0	+240	+250	+260	+260
Annual net	−9 200	+2 650	+2 850	+3 050	+3 030
Cumulative net	−9 200	−6 550	−3 700	−650	+2 380

13.2 Energy Cost and Pumping Optimisation

Energy for pumping is typically the largest single operating cost. Three measures cut energy use without sacrificing crop performance: oversizing main and sub-main pipes by one diameter step (lower velocity → lower head loss → lower kWh per m^3); using variable-frequency drives on pumps to match flow to actual demand; and irrigating at night when off-peak tariffs apply (often 30–50 % discount in Ukraine). Together these measures can cut pumping energy by 20–40 % over the season.

13.3 Water Rights, Regulations, and Quality Standards

Irrigation water abstraction in Ukraine is regulated by the Water Code (Vodnyi Kodeks), with permits issued by State Water Resources Agency (Derzhvodahentstvo) basin authorities. Larger abstractors (above 5 m^3/h from surface or groundwater sources) are required to install metering equipment and report quarterly. Water quality standards for irrigation are set in DSTU 2730:2015 (the updated successor to the 1994 standard), which specifies maximum electrical conductivity, sodium adsorption ratio, and concentrations of toxic ions; growers using surface water must verify compliance each season.

Within the framework of Ukraine's European integration, the Nitrates Directive and the Water Framework Directive set additional limits on nitrogen application rates and on agricultural impact on water bodies. Fertigation through drip irrigation is well aligned with these directives because it allows precise dose control and minimises leaching losses.

Appendix A: Worked Irrigation Schedule Examples

A.1 Onion under drip in Kherson oblast

Field of 1 hectare, silt-loam soil, FC = 31 % v/v, PWP = 13 % v/v, AWC = 180 mm/m. Onion planted 15 April, harvested 25 August (132 days). Drip system delivers 4.8 mm/h instantaneously through twin laterals at 0.2 m emitter spacing.

Table 23 – Seasonal irrigation schedule for storage onion (1 ha, Kherson, drip).

Decade	Kc	ETo (mm)	ETc (mm)	Eff. rain (mm)	Irrig. (mm)	Run-time (h)
1 May	0.50	35	18	10	8	1.7
2 May	0.55	42	23	12	11	2.3
3 May	0.65	47	31	12	19	4.0
1 Jun	0.85	50	43	15	28	5.8
2 Jun	1.00	52	52	10	42	8.8
3 Jun	1.05	54	57	15	42	8.8
1 Jul	1.10	60	66	10	56	11.7
2 Jul	1.10	62	68	5	63	13.1
3 Jul	1.05	64	67	5	62	12.9
1 Aug	1.00	58	58	10	48	10.0
2 Aug	0.85	55	47	10	37	7.7
3 Aug	0.65	48	31	10	21	4.4
Total	—	627	561	124	437	91.2

A.2 Cabbage scheduling sheet (Forest-Steppe, sprinkler + drip)

Field of 0.5 hectare, sandy-loam soil, transplanted cabbage variety 'Slava' (storage). Planting 15 May, harvest 5 September. Single drip line per row, emitter 2 L/h at 0.5 m, application rate 2.4 mm/h.

Table 24 – Decade-by-decade water budget for cabbage, central Ukraine (0.5 ha).

Decade	Kc	ETo (mm)	ETc (mm)	Eff. rain (mm)	Irrig. (mm)	Volume (m³)
3 May	0.60	40	24	18	6	30
1 Jun	0.75	47	35	20	15	75
2 Jun	0.95	50	47	20	27	135
3 Jun	1.05	52	55	15	40	200
1 Jul	1.05	58	61	18	43	215
2 Jul	1.05	60	63	10	53	265
3 Jul	1.05	60	63	12	51	255
1 Aug	1.00	55	55	12	43	215
2 Aug	0.95	50	48	10	38	190
3 Aug	0.85	45	38	10	28	140
1 Sep	0.75	32	24	10	14	70
Total	—	549	513	155	358	1 790

Appendix B: Useful Conversions and Constants

Table 25 – Common irrigation unit conversions.

From	To	Multiply by
mm of water depth	m^3 per hectare	10
m^3 per hectare	mm of water depth	0.1
L per second	m^3 per hour	3.6
m^3 per hour per hectare	mm per hour	0.1
bar	metres of water head	10.2
psi	bar	0.0689
psi	metres of water head	0.7031
dS/m (EC)	mg/L total dissolved solids (approx.)	640
acre	hectare	0.4047
gallon (US) per minute	litres per second	0.0631
inch (rainfall)	mm	25.4

Table 26 – Reference values for soil and water properties.

Property	Typical value	Unit
Density of water (4 °C)	1 000	kg/m^3
Specific heat of water	4.186	kJ/(kg·K)
Latent heat of vaporisation (20 °C)	2 453	kJ/kg
Atmospheric pressure (sea level)	101.325	kPa
Acceleration of gravity	9.81	m/s^2
Bulk density (typical agricultural soil)	1.2–1.5	g/cm^3

Property	Typical value	Unit
Field capacity (sandy loam)	18–22	% v/v
Field capacity (silt loam)	28–34	% v/v
Field capacity (clay loam)	33–40	% v/v
Permanent wilting point (sandy loam)	8–12	% v/v
Permanent wilting point (silt loam)	12–15	% v/v
Permanent wilting point (clay loam)	17–20	% v/v

Appendix C: Glossary

Table 27 Definitions of the irrigation and fertigation terminology used in this manual.

Term	Definition
Available water (AW)	Water held in the soil between field capacity and permanent wilting point; usable by the plant.
Crop coefficient (Kc)	Ratio of crop evapotranspiration to reference evapotranspiration; varies with growth stage.
Deficit irrigation	Deliberate application of less than full ETc, at stages tolerant of stress.
Drip irrigation	Low-pressure micro-irrigation delivering water at emitters spaced along laterals.
Effective rainfall	Share of precipitation that infiltrates and is stored in the root zone.
Emitter	Outlet on a drip lateral that meters water flow to the soil.
ETo	Reference evapotranspiration of a hypothetical 0.12 m grass; depends only on weather.
ETc	Crop evapotranspiration; ETc = Kc × ETo.
Fertigation	Application of fertilizer dissolved in irrigation water.
Field capacity (FC)	Soil moisture retained after free drainage has ceased; upper limit of plant-available water.
IWUE	Irrigation water-use efficiency = marketable yield / irrigation applied (kg/m^3).
Leaching fraction	Share of applied water that drains below the root zone, carrying salts.
Permanent wilting point (PWP)	Soil moisture below which plants cannot recover from wilting; lower limit of AW.
Pressure-compensating emitter	Emitter that delivers constant flow over a range of pressures.
Regulated deficit irrigation (RDI)	Strategy of applying less water at non-critical stages.
SDI	Subsurface drip irrigation; laterals buried 15–35 cm below surface.

Term	Definition
Soil water deficit (SWD)	Difference between current root-zone water and field capacity, in mm.
Tensiometer	Instrument measuring soil matric potential (suction) in centibars or kPa.
TAW	Total available water in the root zone (mm); the maximum SWD before stress.
VPD	Vapour pressure deficit; difference between saturation and actual vapour pressure of air.
Wetted bulb	3-D volume of soil wetted by a single drip emitter.

Appendix D: Useful Contacts and Further Reading

D.1 Ukrainian institutions

- State Agency of Water Resources of Ukraine (Derzhvodahentstvo) – www.davr.gov.ua – issues abstraction permits, maintains regional basin offices, publishes Kakhovka and Dnipro-Inhulets system bulletins.
- National University of Life and Environmental Sciences of Ukraine (NUBiP), Faculty of Land Reclamation and Water Management, Kyiv – the main Ukrainian academic centre for irrigation research and graduate training.
- Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine, Kherson – field research, demonstration trials, regional recommendations.
- Ukrainian Agribusiness Club (UCAB) – analytics on irrigation investment, financing programmes, export markets.

D.2 International resources

- FAO Land and Water Division – publications and free software (CropWat, AquaCrop, ClimWat) for irrigation planning. www.fao.org/land-water.
- International Commission on Irrigation and Drainage (ICID) – New Delhi; technical publications and the Ukrainian National Committee.
- EBRD Green Economy Financing Facility – co-financing for irrigation modernisation in Ukraine.
- Oregon State University Extension – widely used English-language drip irrigation guides for onion, carrot, and beet.

D.3 Software and apps

- CropWat 8.0 (FAO) – decision support for irrigation scheduling based on crop, soil, climate.
- AquaCrop (FAO) – crop water productivity simulation under different irrigation strategies.
- ETo Calculator (FAO) – Penman–Monteith computation from weather station data.
- Netafim NetBeat, Naandanjain DripWise, Rivulis Manna – commercial cloud platforms for fertigation control.

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