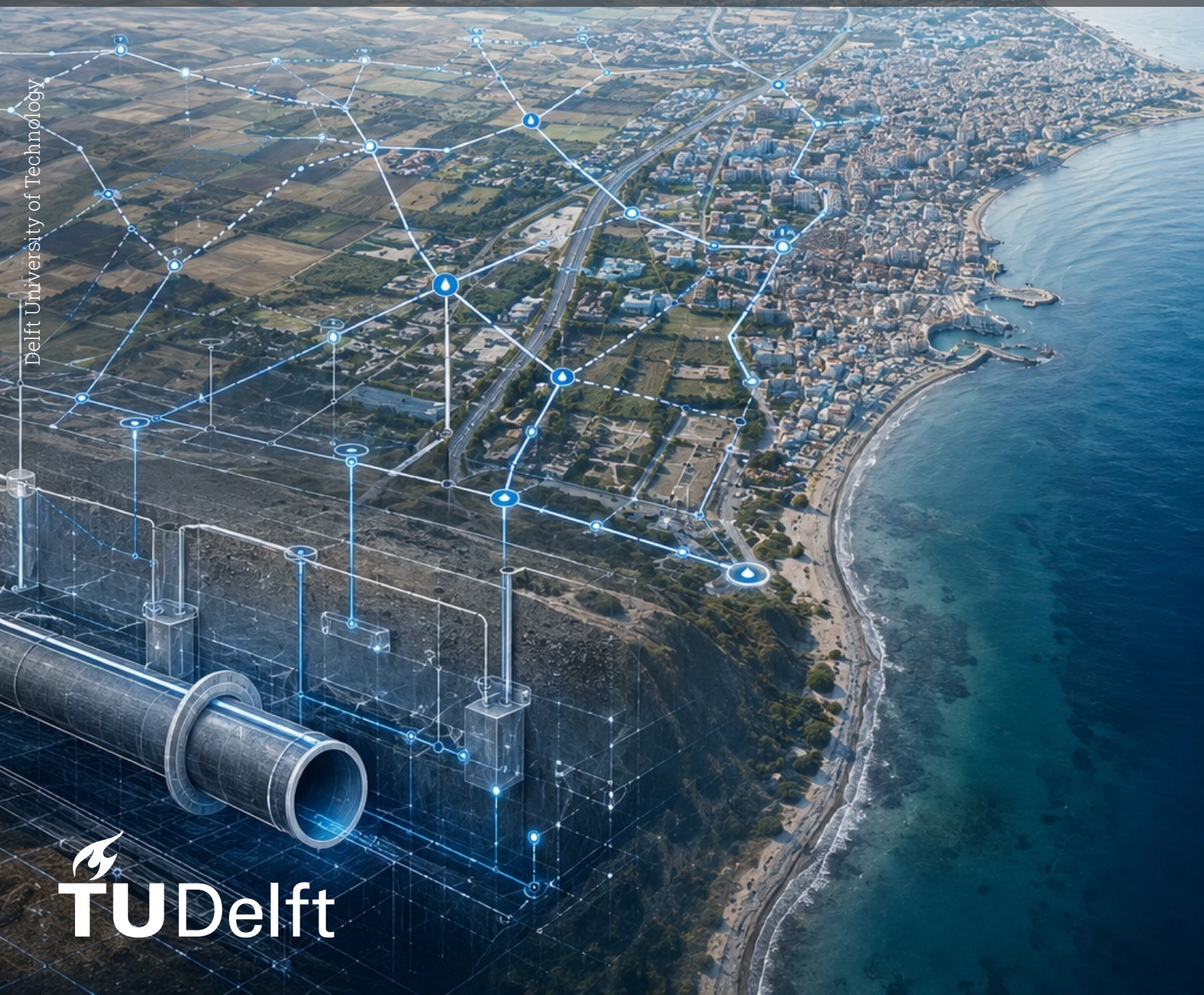
Wastewater Network Expansion Optimisation in the Larnaka District, Cyprus

A spatial graph-based approach to budget-constrained sewer infrastructure planning

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Preface

With this thesis, a six-month research period comes to an end, but more importantly, so does the student phase of my life. It has been an intense and meaningful experience, and one that I will look back on with gratitude.

I would like to thank Petra and Martijn for their guidance throughout these six months. I greatly appreciated your supervision, your advice, and the support you offered, especially during the more difficult moments of the research process.

I would also like to thank Dimitris and the District Local Government Organisation of Larnaka for making this research possible and for providing the information and data needed to carry out the thesis.

I would also like to thank all the people who have been part of these months and of the years that preceded them. Some of you appeared only briefly, while others became constant presences, but all of you contributed in some way to a story that I will remember fondly.

My deepest gratitude goes to my parents, whose support made this entire journey possible.

I wish all of you the very best for whatever lies ahead, and I hope that I, too, will find what I am looking for.

Luca Marigliano
Delft, August 2026

Summary

Wastewater collection and treatment systems are essential for public health, environmental protection, and regulatory compliance. Their expansion, however, is not simply a matter of extending pipes toward unserved areas. Wastewater demand is distributed across buildings and settlements, while the collection network must combine these sources into shared corridors leading toward treatment. The cost and structure of the resulting system therefore depend on settlement density, distance, available construction routes, and the extent to which different branches can share common pipes. As expansion moves from dense urban areas toward smaller or more peripheral settlements, each additional kilometre of sewer tends to serve fewer inhabitants, causing the cost of further coverage to increase. In flat or low-lying areas, gravity conveyance may also require deep excavation or pumping stations, adding capital cost and operational complexity. Wastewater expansion is consequently both an engineering problem and a spatial investment decision: planners must decide which demand should be served first, how limited funding should be distributed, and when the cost of additional coverage becomes disproportionate.

The Larnaka District in Cyprus presents this type of planning challenge. The southern part of the study area is associated with the existing wastewater system centred on Meneou, referred to as WWTP1, while the northern municipalities of Aradippou, Livadia, Pyla, Kellia, and Oroklini remain unserved or only partially served by collective wastewater infrastructure. The need for expansion has become more pressing under Directive (EU) 2024/3019, which reduces the threshold for mandatory wastewater collection and treatment from 2,000 to 1,000 population equivalent and therefore brings smaller agglomerations more directly into the planning process. The District Organisation must consequently determine how the five northern municipalities could be connected to a new treatment endpoint, how much population can be served within a sewer-network budget of approximately EUR 100–150 million, and how aggregate coverage should be balanced against the service of smaller or more peripheral municipalities.

To support this decision, the thesis develops a spatial graph-based planning framework for generating, assessing, and comparing wastewater network expansion configurations. The framework represents roads as possible construction corridors, distributes municipal population across building footprints and road-network nodes, incorporates existing conduits and pumping stations as the brownfield infrastructure context, and uses terrain elevation to screen the generated layouts for likely pumping requirements. A planning-level northern treatment endpoint, referred to as WWTP2, is selected through a rule-based screening process and used as the common root for all configurations.

The framework is positioned between master planning and detailed engineering design. It does not produce construction-ready pipe diameters, invert levels, pump capacities, or treatment-plant specifications. Instead, it compares strategic expansion directions before a preferred layout is developed through detailed hydraulic design.

Five configurations are generated. Rooted Dijkstra and Prim–Steiner are non-budgeted full-urban-coverage references that show the approximate infrastructure required to connect all modelled urban demand. Shared-trunk, Urban-priority, and Municipality-targets operate under a common new-pipe ceiling of approximately 250 km, corresponding to EUR 100 million in pipe construction cost. Shared-trunk prioritises population gain along shared corridors, Urban-priority focuses on dense urban clusters, and Municipality-targets applies staged municipal coverage objectives. The layouts are then reconciled with the existing WWTP1/WWTP2 infrastructure context and screened for likely pumping requirements.

The comparison first shows that full urban coverage can be generated within the planning-level model, but at a cost well above the available financial envelope. Rooted Dijkstra requires 494.6 km of new pipe and reaches a total capital cost of EUR 242.9 million after including 30 retained pumping-station candidates. Prim–Steiner reaches the same 100% urban coverage through a more compact network of 399.8 km, with 26 retained pumping-station candidates and a total capital cost of EUR 198.9 million.

Compared with Rooted Dijkstra, it reduces network length by 94.8 km and total capital cost by EUR 44.0 million, demonstrating the value of shared network branches. Nevertheless, even this more compact full-coverage configuration remains EUR 48.9 million above the upper end of the budget.

The three budget-constrained configurations achieve near-complete aggregate coverage within a much narrower total-cost range. Shared-trunk reaches the highest urban coverage at 97.5%, serving 106,360 inhabitants at a total capital cost of EUR 130.0 million. Urban-priority reaches 96.4% coverage and has the lowest total cost at EUR 127.0 million, while Municipality-targets reaches 95.7% coverage at EUR 130.0 million. Their principal difference is therefore not the amount of investment required, but how that investment is distributed across the northern municipalities.

Shared-trunk maximises aggregate coverage through corridor-sharing efficiency, but its minimum municipal coverage is only 35.3%, with a municipal coverage standard deviation of 24.4 percentage points. Urban-priority has a municipal dispersion of 31.1 percentage points and a minimum coverage of 31.9%. Municipality-targets reduces the dispersion to 8.5 percentage points and raises minimum municipal coverage to 75.9%. In Pyla, coverage increases from 35.3% under Shared-trunk and Urban-priority to 87.9% under Municipality-targets. This more balanced distribution is obtained at the cost of only 1.8 percentage points of aggregate coverage, equivalent to 1,869 inhabitants.

The results therefore reveal a trade-off between aggregate efficiency and municipal distribution. This distinction matters because wastewater obligations apply to individual agglomerations rather than only to the district-wide total. A configuration with high aggregate coverage may still leave a relevant settlement insufficiently served, as demonstrated by the limited coverage of Pyla under the two efficiency-oriented configurations.

The comparison with the full-coverage references also shows that the final percentage points of coverage are disproportionately expensive. Increasing urban coverage from 97.5% under Shared-trunk to 100% under Prim–Steiner raises total capital cost from EUR 130.0 million to EUR 198.9 million: an increase of EUR 68.9 million for the remaining 2.5 percentage points. Although these configurations are generated independently and do not represent successive construction phases, the comparison shows that connecting the remaining peripheral demand requires substantially more pipe and investment.

Pumping requirements further affect affordability. Although the three budget-constrained configurations respect the EUR 100 million pipe-construction ceiling, their total capital costs rise to EUR 127.0–130.0 million once the estimated cost of 18–20 new pumping stations is included. In the flat terrain of Larnaka, pipe length alone would therefore underestimate the likely investment requirement.

On this basis, the District Organisation should not pursue immediate full urban coverage as the first investment objective. A budget-constrained configuration should instead form the basis of the first investment phase. Among the available directions, a municipality-balanced logic, or a hybrid combining Shared-trunk efficiency with minimum municipal coverage floors, provides the most defensible basis for further development. This would retain the benefits of shared corridors while reducing the risk that smaller or more peripheral municipalities remain insufficiently served.

The next planning step should therefore be to refine this hybrid direction rather than selecting one of the five outputs directly as a final design. Before implementation, detailed hydraulic modelling and a refined cost assessment should verify the network layout, pumping requirements, treatment capacity, and the role of the existing infrastructure. The remaining peripheral connections may then be considered in later phases as additional funding, updated demand information, and further technical assessment become available.

The framework remains a strategic screening instrument rather than a final sewer design. Its main contribution is to integrate spatial demand, corridor-based routing, alternative investment priorities, brownfield interpretation, municipal distribution, and pumping-aware cost assessment within one planning workflow. For Larnaka, it provides a clear strategic direction: pursue a financially realistic first phase, protect minimum municipal service levels, and defer the disproportionately expensive final connections until their technical and financial justification has been assessed in greater detail.

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Nomenclature

Abbreviations

Table 1 lists the abbreviations used throughout this thesis.

Table 1: Abbreviations

Abbreviation	Definition
CAPEX	Capital Expenditure
CYSTAT	Statistical Service of Cyprus
DEM	Digital Elevation Model
EIB	European Investment Bank
EPSG	European Petroleum Survey Group (coordinate reference code)
EU	European Union
GLO-30	Copernicus Global DEM at 30 m resolution
ML	Machine Learning
OSM	OpenStreetMap
PE	Population Equivalent
PS	Pumping Station
SQ	Sub-Question
UTM	Universal Transverse Mercator
WWTP	Wastewater Treatment Plant
WWTP1	Existing southern wastewater treatment system centred on Meneou
WWTP2	Proposed northern wastewater treatment endpoint

Notation

Tables 2–4 define, respectively, the sets, the parameters, and the variables and functions used.

Table 2: Sets

Symbol	Definition
N	Set of graph nodes
N'	Set of nodes incident to the selected new-pipe edges E'
E	Set of graph edges, including candidate construction corridors and existing conduits, $E \subseteq \{(i,j) \mid i,j \in N\}$
E'	Set of new edges selected in a given configuration, $E' \subseteq E$
M	Set of municipalities
M^{N}	Set of northern expansion municipalities, $M^{\mathrm{N}} \subseteq M$
B	Set of building footprints
B_m	Set of buildings in municipality m, $B_m \subseteq B$, $\forall m \in M$
B_i	Set of buildings aggregated to node i, $\forall i \in N$
D	Set of demand nodes, $D \subseteq N$
D^+	Set of demand nodes with positive assigned population before urban-footprint filtering, $D^+ \subseteq D$
T	Set of modelled urban demand terminals used by the expansion algorithms, $T \subseteq D^+$
T_m	Set of modelled urban demand terminals located in municipality m, $T_m \subseteq T$, $\forall m \in M$
S	Set of served urban demand terminals in a given configuration, $S \subseteq T$
S_{tot}	Set of positive-population demand nodes treated as served in the final configuration interpretation, including generated-network and brownfield service components, $S_{\mathrm{tot}} \subseteq D^+$
ε_j	Set of new edges connecting candidate j to the current network, $\varepsilon_j \subseteq E \setminus E'$
ρ_j	Set of nodes on the connecting path of candidate j, $\rho_j \subseteq N$
γ_j	Set of demand nodes in the cluster of candidate j, $\gamma_j \subseteq T$
J^{feas}	Set of WWTP2 candidates satisfying the geographic, urban-clearance, road-connectivity, snapping-distance, and low-elevation requirements
K	Set of candidate pumping-station locations
K^{ex}	Set of existing pumping stations used to scale the optional-candidate cap
K'	Set of retained pumping stations, $K' \subseteq K$
r	WWTP2 root node representing the treatment endpoint, $r \in N$

Table 3: Parameters

Symbol	Definition	Unit
ℓ_e	Length of edge e	m
a_b	Footprint area of building b	m^2
w_m	Population of municipality m	inhab.
q	Per-capita wastewater generation rate	$\mathrm{L\,cap^{-1}\,day^{-1}}$
c	Unit pipe construction cost	$\mathrm{EUR\,m^{-1}}$
h	Capital cost per new pumping station	EUR
β	Total sewer-network budget	EUR
v	Design self-cleansing velocity	$\mathrm{m\,s^{-1}}$
n	Manning roughness coefficient	–
d	Representative design pipe diameter	m
R	Hydraulic radius at the representative design diameter	m
$\delta_{\max}$	Maximum admissible gravity cover depth	m
y_{north}	Minimum admissible northing used in WWTP2 endpoint screening	m
y_{pref}	Preferred northing used in WWTP2 candidate ranking	m
$\eta_{0.05}$	5th percentile of ground elevation among geographically feasible WWTP2 candidates	m a.s.l.
$\eta_{0.95}$	95th percentile of ground elevation among geographically feasible WWTP2 candidates	m a.s.l.

Table 4: Variables and functions

Symbol	Definition	Unit
p_b	Population assigned to building b	inhab.
p_i	Population assigned to node i	inhab.
f_i	Wastewater load at node i	$\mathrm{m}^3\,\mathrm{day}^{-1}$
$\ell(E')$	Total length of the selected new-edge set E'	m
C	Pipe-construction cost of a configuration	EUR
z	Total cost of a configuration, including new pipes and retained new pumping stations	EUR
u	Total cost per inhabitant served	$\mathrm{EUR\,inhab.}^{-1}$
$\lambda_{\max}$	Maximum admissible new-pipe length under the budget constraint	m
Δc_j	Marginal construction cost of connecting candidate j	EUR
Δp_j	Population gain obtained by connecting candidate j	inhab.
g_j	Benefit–cost score of candidate j	$\mathrm{inhab.\,EUR}^{-1}$
s_j	WWTP2 site score of candidate j	m
d_j^{cent}	Euclidean distance between WWTP2 candidate j and the population-weighted centroid of northern urban demand	m
d_j^{pref}	Absolute northing difference between WWTP2 candidate j and the preferred northing position	m
y_j	Projected northing coordinate of WWTP2 candidate j	m
η_j	Ground elevation of WWTP2 candidate j	m a.s.l.
$\widetilde{\eta}_j$	Normalised elevation of WWTP2 candidate j, clipped to the interval $[0, 1]$	–
π_j^{elev}	Elevation penalty included in the WWTP2 site score	m
$s_{\min}$	Minimum gravity slope	–
δ_i	Required excavation depth at node i	m
I_i	Required pipe invert elevation at node i	m a.s.l.
η_i	Ground elevation at graph node i	m a.s.l.
κ	Number of connected components in the selected new-pipe layout	–
μ	Cyclomatic number of the selected new-pipe layout	–
x_u	Urban population coverage of a configuration, computed over T	%
x_m	Municipal urban population coverage of municipality m	%
x_{tot}	Total-population coverage of a configuration, computed over D^+	%
$\bar{x}$	Unweighted mean municipal urban coverage across the northern municipalities	%
σ_x	Standard deviation of municipal urban coverage across the northern municipalities	percentage points
$x^{\min}$	Minimum municipal urban coverage among the northern municipalities	%

1

Introduction and Problem Framing

This chapter introduces the background and motivation of the research. It first describes the wastewater infrastructure challenge in general terms, with particular attention to environmental protection, regulatory pressure, and the spatial complexity of extending collective sewerage to unserved or partially served communities. It then introduces the Larnaka District as the case study through which this challenge is examined, framing the problem as a strategic wastewater network planning challenge for the northern part of the district, where a new collective wastewater system is required for Aradippou, Livadia, Pyla, Kellia, and Oroklini. Finally, it outlines the structure of the thesis.

1.1. Wastewater Infrastructure Challenges

Access to functional wastewater collection and treatment systems is essential for public health, environmental protection, and regulatory compliance in urban and peri-urban areas. Although wastewater treatment coverage has improved substantially across Europe since the adoption of the Urban Waste Water Treatment Directive in 1991, many smaller settlements and peri-urban communities still rely on onsite wastewater systems, such as septic tanks, rather than collective sewerage networks [1]. Where these systems are inadequate, poorly maintained, or located in environmentally sensitive areas, they can contribute to groundwater and surface-water contamination through the release of nutrients, organic matter, and pathogens [2]. The absence of collective wastewater infrastructure therefore remains a significant challenge for water quality governance, land-use planning, and long-term environmental protection [3].

Extending collective sewerage is, in itself, a demanding spatial planning problem. Wastewater is generated by dispersed households and settlements, and connecting them to treatment requires physically constructible corridors whose length and cost tend to grow rapidly as demand becomes more dispersed or the local terrain less favourable to gravity conveyance [4], [5]. In flat or low-lying areas in particular, gravity flow alone is often insufficient, so networks must combine gravity sewers with pumping stations and pressure mains, adding both capital and operational cost. Such expansion, moreover, rarely takes place on a blank slate: planners must integrate existing sewers, pumping stations, and treatment plants, and increasingly must do so under binding regulatory targets and limited investment budgets [6]. Deciding where to build new pipes, which communities to prioritise, and where pumping is required therefore has long-term consequences for cost, service coverage, and operational flexibility.

1.2. The Larnaka District as a Case Study

This challenge is particularly relevant in the Larnaka District in Cyprus, where several communities remain unserved or only partially served by collective wastewater collection infrastructure. Approximately thirty surrounding communities still lack adequate sewerage infrastructure, and a subset of these settlements exceeds 1000 population equivalent (PE), placing them within the scope of strengthened European wastewater requirements [7]. Directive (EU) 2024/3019 lowers the threshold for mandatory wastewater collection and treatment obligations from $2000\,\mathrm{PE}$ to $1000\,\mathrm{PE}$, requiring agglomerations

above this threshold to be connected to collecting systems and secondary treatment within defined deadlines [8]. For Larnaka, these regulatory obligations create a practical infrastructure planning problem: wastewater services must be expanded in a way that is technically plausible, financially realistic, and aligned with future compliance requirements.

The wider Larnaka study area includes Larnaka, Aradippou, Livadia, Oroklini, Kellia, Dromolaxia–Meneou, Perivolia, Kiti, and Pyla, which together represent approximately $110\,000$ inhabitants and around $38\,000$ families. The population is distributed across dense urban areas, peri-urban settlements, and smaller communities, creating a heterogeneous spatial demand pattern for wastewater collection. However, the infrastructure challenge is not uniform across the district. The southern part of the study area is already served, at least in its main urbanised areas, by the existing wastewater treatment plant (WWTP) in Meneou and its associated sewerage network. By contrast, the northern and north-eastern municipalities, particularly Aradippou, Livadia, Pyla, Kellia, and Oroklini, require a dedicated strategy for collective wastewater collection and treatment.

The Meneou wastewater treatment plant is therefore a central asset in the existing district system, but it does not provide a complete solution for the northern municipalities. Extending all future wastewater flows from the northern municipalities toward Meneou would require long conveyance routes across the district, potentially increasing pipe length, pumping requirements, operational complexity, and exposure to future capacity constraints. The planning issue is therefore better understood as a two-system configuration: an existing southern system centred on Meneou and a proposed northern system requiring its own collection network and treatment endpoint.

The physical characteristics of the district further complicate this planning problem. Much of the Larnaka area is characterised by relatively flat terrain near sea level. In such conditions, gravity-only conveyance may become difficult over long distances or across poorly graded routes. Wastewater systems may therefore require a combination of gravity sewers, pumping stations, and pressure mains, increasing both capital expenditure and operational complexity [7]. The feasibility of the northern wastewater system consequently depends not only on the distance between demand areas and the treatment endpoint, but also on topography, available corridors, existing sewer locations, flow direction, and likely pumping-station requirements.

At the same time, the Larnaka District is undergoing a significant wastewater investment programme, with the European Investment Bank committing EUR 230 million toward wastewater management and sewerage network expansion across the district [9]. This creates an opportunity to improve wastewater service provision, but it also increases the importance of careful spatial planning. Decisions on where to construct new pipes, how to connect currently underserved municipalities, how to account for existing sewerage assets, and where pumping infrastructure may be required can have long-term consequences for cost, service coverage, and operational flexibility.

Taken together, these conditions define a spatial wastewater infrastructure planning problem under regulatory, technical, and financial constraints. The northern municipalities require a network configuration that can connect distributed wastewater demand to a treatment endpoint through feasible corridors while limiting unnecessary pipe length and identifying areas where pumping may be required. The aim is not to produce a final hydraulic design, but to support strategic decision-making by comparing technically plausible and spatially efficient wastewater network configurations for the northern part of the Larnaka District.

1.3. Thesis Structure

The thesis is organised to move from the general wastewater infrastructure challenge to the specific modelling approach developed for the Larnaka District, and then to its results and implications. After this introductory chapter, Chapter 2 reviews the literature on spatial wastewater demand, corridor-based network representation, graph-based and budget-constrained optimisation, pumping-related feasibility screening, and the integration of existing sewer assets, and identifies the research gap that motivates an integrated planning approach for the northern Larnaka wastewater system.

Chapter 3 then introduces the real-world problem: it presents the District Local Government Organisation of Larnaka as the principal stakeholder, characterises the Larnaka case and its two-system struc-

ture around the existing southern system (WWTP1) and the proposed northern endpoint (WWTP2), and derives the performance metrics used throughout the thesis. Building on this, Chapter 4 translates the research gap and the stakeholder-defined metrics into the main research question and five sub-questions, each corresponding to one step of the modelling workflow.

Chapter 5 defines the data on which the workflow operates, distinguishing the datasets and numeric parameters provided by the District Organisation from those obtained externally, and states the modelling assumptions adopted to bridge the remaining gaps. Chapter 6 then presents the five-phase modelling approach: the construction of the baseline spatial graph, the rule-based positioning of the WWTP2 endpoint, the generation of non-budgeted and budget-constrained network expansion configurations with the reconciliation of existing assets between WWTP1 and WWTP2, the pumping-feasibility screening, and the evaluation metrics used to compare the configurations, together with the verification and validation strategy.

Chapter 7 reports the results of each phase, including the demand representation, the selected WWTP2 endpoint, the five generated networks, the brownfield allocation, the pumping-station candidates, and the integrated configuration comparison. Finally, Chapter 8 interprets the configuration comparison, discusses the broader implications and transferability of the approach, its data-related and method-intrinsic limitations, and the resulting recommendations for the Larnaka District, and Chapter 9 answers the research questions and summarises the scientific and societal contributions and directions for future research. Appendix A documents the use of AI tools, Appendix B describes the code repository, and Appendix C reports the verification and validation checks.

2

Literature Review and Research Gap

This chapter reviews the literature relevant to strategic wastewater network planning in the Larnaka District. Building on the problem framing developed in Chapter 1, the review focuses on the concepts needed to support a spatial graph-based approach to sewer network expansion. The chapter first discusses spatial wastewater demand and service configuration, then examines corridor-based network representation, graph-based and budget-constrained optimisation, pumping-related feasibility screening, and the integration of existing sewer assets. The purpose is not to describe the implementation of the model, but to identify the research gap that motivates an integrated planning approach for the proposed northern wastewater system.

2.1. Spatial Wastewater Demand and Service Configuration

As introduced in Chapter 1, wastewater infrastructure planning is fundamentally spatial. Wastewater is generated by households, buildings, neighbourhoods, and settlements, while collection systems must physically connect these distributed sources to treatment infrastructure. Spatial estimates of wastewater production show that wastewater management cannot be understood only through national or regional totals, because the location and density of wastewater sources strongly influence the type, length, and cost of the infrastructure required to collect and treat wastewater [1]. This is particularly relevant in districts where demand is distributed across dense urban areas, peri-urban settlements, and smaller communities.

The suitability of onsite wastewater systems varies considerably across these spatial contexts. Septic tanks and similar arrangements may be appropriate in some low-density areas, but their performance depends on soil characteristics, groundwater depth, hydraulic loading, maintenance practices, and local monitoring capacity. The literature identifies nutrient loading as a particularly important concern: sustained discharges from onsite systems can measurably increase eutrophication risks in receiving waters, including in low-density rural catchments [10]. These risks are amplified in coastal and shallow-aquifer settings, where nitrogen released below the soil treatment area can be transported through groundwater and discharged into surface and coastal waters, making the density of onsite systems a recognised driver of coastal water-quality degradation [11]. The suitability of onsite systems therefore depends not only on settlement density, but also on hydrogeological conditions, environmental sensitivity, maintenance capacity, and institutional oversight [2], [3].

Wastewater planning literature commonly distinguishes between centralised, decentralised, and hybrid service configurations. Centralised systems convey wastewater from multiple demand areas to one or more larger wastewater treatment plants. Their advantages include economies of scale, professional operation, stronger regulatory oversight, and the possibility of advanced treatment and reuse [12]. However, centralised systems can become expensive and technically complex when settlements are dispersed, because the cost of sewerage is strongly affected by the length of pipe required per connected inhabitant [4]. Decentralised systems can reduce conveyance distances by treating wastewater closer to the point of generation and may support phased implementation at smaller spatial scales [13].

However, they also require reliable local operation, maintenance, monitoring, and institutional capacity [3], [12].

Several authors therefore argue that wastewater planning should not be reduced to a simple choice between centralised and decentralised systems. Hybrid configurations may be more appropriate where dense urban areas, peri-urban settlements, and smaller communities coexist within the same district [13], [14]. For the Larnaka case, this literature is relevant because it highlights the importance of spatial demand distribution, distance, density, and governance capacity. The key issue is not to compare all possible treatment configurations in abstract terms, but to develop a planning approach that can represent distributed wastewater demand and evaluate how it can be connected through a technically plausible collection network.

In this context, the treatment endpoint should be understood as a network-defining assumption. Its location affects the length of trunk connections, the direction of conveyance, the possibility of shared corridors, and the likelihood of pumping requirements. Wastewater optimisation studies that consider treatment, location, and transport together show that treatment decisions and spatial conveyance decisions can be strongly interdependent [15]. However, in constrained planning contexts, the problem is often not a full site-suitability analysis of all possible treatment plant locations. Instead, the practical planning task is to evaluate how a proposed or constrained treatment endpoint affects the configuration, cost, and feasibility of the corresponding collection network.

2.2. Corridor-Based Representation of Sewer Networks

Because sewer systems are spatial infrastructures, their planning depends on how geography is represented. Straight-line distance between demand points and treatment infrastructure is rarely sufficient, because sewers normally follow physically constructible corridors such as roads, public rights-of-way, or other accessible alignments. A direct geometric connection may appear short, but may not correspond to a realistic construction path. Corridor-based representations therefore provide a more meaningful basis for estimating pipe length, construction cost, and possible network layouts.

Graph-based representations are widely used to model infrastructure networks. In a graph, nodes represent relevant locations and edges represent possible connections between them. For sewer network planning, nodes can represent road junctions, demand points, connection points, pumping-station candidates, or treatment endpoints, while edges can represent possible pipe corridors. In urban analysis, graph-based tools have been widely applied to street networks, accessibility analysis, and infrastructure-related spatial modelling [16], [17]. These approaches are relevant to sewer planning because road networks and other corridor systems often constrain where new sewer pipes can realistically be constructed.

However, a wastewater-specific graph must represent more than generic connectivity. It must distinguish wastewater demand from simple geographic nodes, and it must differentiate between existing sewer assets and potential new pipes. These two types of infrastructure have different planning meanings. Existing assets may provide connection opportunities, constraints, or reference points for future expansion, while candidate corridors represent possible future investments. Spatially explicit sewer-generation models similarly build the network from demand, terrain, and urban structure rather than from geometry alone [18]; a planning-level sewer model must therefore connect spatially distributed demand to treatment infrastructure while accounting for both existing and potential future network elements.

This makes sewer network planning different from a standard shortest-path problem. A shortest path can identify the minimum-cost route between two points, but a wastewater collection system must connect multiple demand locations, share corridors where possible, respect existing infrastructure context, and balance total coverage against investment cost. The representation of demand points, corridors, treatment endpoints, existing pipes, and potential new pipes within a single graph is therefore a necessary step before alternative network configurations can be compared.

For the Larnaka case, corridor-based graph representation is particularly important because the northern wastewater system must serve several municipalities distributed across a heterogeneous spatial area. The graph must allow the analysis to estimate not only how far each demand area is from the

treatment endpoint, but also how different demand areas can be connected through shared corridors and how these choices affect total pipe length, cost, coverage, and feasibility. A corridor-based graph therefore provides the structural basis for comparing alternative wastewater network expansion strategies.

2.3. Graph-Based Network Expansion and Budget-Constrained Optimisation

Optimisation methods provide a way to formalise infrastructure planning decisions. In water and wastewater systems, optimisation has been used for treatment technology selection, facility location, pipe design, rehabilitation planning, resource recovery, and operational control [6]. Detailed sewer design literature also includes methods for selecting pipe diameters, slopes, and layouts while satisfying hydraulic constraints [5], [19]. These approaches are important, but many of them address either detailed hydraulic design, rehabilitation of an existing network, treatment-side optimisation, or planning within a predefined catchment.

Strategic sewer network expansion occupies an intermediate position between high-level wastewater planning and detailed engineering design. At this stage, planners may not yet know the final pipe diameters, invert levels, pumping-station specifications, or hydraulic profiles. However, they still need to compare where new pipes could be constructed, how much population could be served, how much network length would be required, and how different layouts perform under budget constraints. A planning-level graph model can support this type of analysis by treating pipe corridors as weighted edges and wastewater demand as a spatially distributed benefit.

Classical graph algorithms provide useful foundations for this type of problem. Shortest-path algorithms identify least-cost routes through weighted graphs and are relevant where individual demand areas must be connected to a treatment endpoint [20], [21]. Tree-based algorithms and spanning-tree concepts are relevant where multiple demand nodes must be connected through a compact network while avoiding unnecessary duplication of corridors [21], [22]. More general network design and constrained forest problems provide a theoretical background for cases where connectivity, cost, and selected terminals must be considered together [23]. These algorithmic foundations do not directly solve the full wastewater planning problem, but they provide the conceptual basis for heuristic methods that combine routing, connection, and cost minimisation.

Budget-constrained network expansion introduces an additional planning layer. When the available budget is insufficient to serve all demand points immediately, the problem becomes not only how to connect demand, but which demand areas should be prioritised. An efficiency-oriented strategy may select areas with high population coverage relative to pipe cost, thereby maximising the number of inhabitants served per unit of investment. However, such an approach may concentrate benefits in dense or nearby areas. A more balanced strategy may allocate infrastructure across municipalities to reduce disparities in service provision, even if total cost efficiency is lower. Infrastructure planning literature recognises that service provision, distributional outcomes, and long-term investment prioritisation are relevant criteria in sustainable urban water management [6], [24].

This distinction is important for wastewater planning in Larnaka. A full-coverage network can provide a useful reference configuration by showing the approximate infrastructure required to serve all relevant demand areas. However, investment constraints require additional configurations that evaluate partial or phased expansion. Different algorithmic logics may therefore be needed: one logic may prioritise the most cost-efficient demand areas, another may emphasise urban concentration, another may support more balanced municipal coverage, and another may favour shared trunk infrastructure. The value of graph-based optimisation at the strategic stage is not that it produces a final engineering design, but that it makes these trade-offs explicit and comparable.

The literature therefore supports the use of graph-based and optimisation-inspired methods for strategic sewer expansion, but it also shows the need for careful interpretation. Shortest paths, tree structures, and budget-constrained selection are useful abstractions, but wastewater infrastructure remains constrained by topography, gravity flow, pumping requirements, existing assets, and local planning conditions. For this reason, graph-based expansion results must be interpreted together with technical

feasibility and brownfield infrastructure context.

2.4. Strategic Feasibility Screening: Topography, Gravity Flow, and Pumping

Wastewater network layouts cannot be evaluated only through horizontal distance, pipe length, or construction cost. Sewer systems are hydraulic infrastructures, and their feasibility depends on terrain, slope, flow direction, pipe depth, flow velocity, and available discharge or treatment points. Conventional gravity sewer systems require sufficient gradient to convey wastewater while avoiding sedimentation and excessive excavation depth. Where natural slopes are favourable, gravity conveyance can be reliable and energy efficient. Where terrain is flat or poorly graded, gravity-only conveyance may require deep trenches, intermediate lifting, or pressure systems [5], [19].

This distinction is important at the planning stage. A route that appears efficient in a spatial graph may be problematic from a hydraulic perspective. A short connection may cross terrain with insufficient gradient, while a longer route may follow a more favourable corridor. Similarly, a treatment endpoint may appear attractive if only distance and pipe length are considered, but less favourable if the resulting collection network requires multiple pumping stations or long pressure mains. Strategic network planning therefore needs to remain aware of hydraulic implications even before detailed engineering design is performed.

Pumping stations are central to this issue. They allow wastewater to be lifted from low-lying areas, transferred across unfavourable terrain, or conveyed through pressure mains when gravity flow is insufficient. However, pumping stations also introduce capital costs, energy consumption, maintenance requirements, operational complexity, and failure risks. Their presence can therefore change the interpretation of a network layout that appears cost-efficient in terms of pipe length alone. In flat regions, or in systems where the treatment endpoint is not naturally aligned with the direction of gravity flow, pumping requirements may become a decisive factor in determining which layouts are practically realistic [5], [19].

The operational literature confirms that pumping stations are important components of wastewater systems. Studies on predictive pump scheduling show that pump operation can affect energy consumption, reliability, and operational alarms [25]. Work on inter-catchment wastewater transfer also shows that pumping stations can become critical assets when wastewater generation and treatment capacity are spatially mismatched [26]. However, these studies mainly address operational optimisation after the network configuration is already known. This is different from the strategic planning question of whether a proposed network is likely to require pumping in the first place.

For this reason, pumping-related analysis at the strategic planning stage should be interpreted as a feasibility screening rather than final pump design. At this level, it may not be possible to determine exact pump capacities, pressure-main dimensions, invert levels, or detailed hydraulic profiles. It is still possible, however, to identify network sections where terrain, slope, long conveyance distance, or excessive excavation depth may indicate the need for pumping infrastructure. Such screening helps prevent layouts from being evaluated only by coverage and pipe cost while hiding major engineering complications.

This is particularly relevant for the Larnaka District because much of the area is characterised by relatively flat coastal terrain. In such conditions, the difference between a spatially efficient route and a hydraulically plausible route can be substantial. A strategic wastewater network model should therefore include pumping-aware interpretation as a complementary layer to graph-based expansion. This does not replace detailed hydraulic modelling, but it improves the planning value of the configuration comparison by identifying where pumping requirements may affect cost, constructability, and operational complexity.

2.5. Brownfield Integration and Existing Sewer Assets

Wastewater infrastructure planning rarely takes place on a blank slate. Existing pipes, pumping stations, treatment plants, and connection points define a brownfield infrastructure context that can influence future expansion. In infrastructure planning, existing assets are commonly treated as long-lived

components that affect maintenance, renewal, coordination, and future investment decisions [6], [27]. In sewer systems, this is especially important because existing pipes and treatment assets may create both opportunities and constraints for future network configuration [5], [19].

Existing sewer assets can influence planning in several ways. They may provide nearby connection points, reduce the need for duplicate infrastructure, or indicate corridors where wastewater infrastructure has already been constructed. At the same time, existing assets may remain functionally linked to a different treatment system, have limited available capacity, or be unsuitable for integration into a new configuration. Brownfield planning therefore requires more than simply mapping existing pipes. Existing infrastructure must be interpreted in relation to service areas, treatment allocation, hydraulic direction, and the intended future role of the system.

For the Larnaka case, this distinction is central. The existing Meneou-based wastewater system remains part of the district-wide infrastructure context, while the northern municipalities require a new collective wastewater system. The planning problem is therefore not to replace the existing system, nor simply to extend every new pipe from the existing southern network. Instead, the challenge is to evaluate how a proposed northern wastewater system can be configured within a district that already contains wastewater infrastructure. Existing sewer assets may provide useful context or connection opportunities, but they may also need to remain associated with the southern system.

This brownfield perspective affects configuration interpretation. A proposed network layout should not be assessed only by total pipe length, construction cost, or population coverage. It should also be evaluated in terms of whether it connects logically to existing infrastructure, avoids unnecessary duplication, respects the functional distinction between the existing southern system and the proposed northern system, and supports a coherent future district-wide wastewater configuration. Existing pumping stations can also provide useful evidence about the type of terrain-network contexts where pumping infrastructure has historically been required, although such evidence should be used as planning support rather than as a substitute for hydraulic design.

Integrating existing assets into a graph-based planning model therefore strengthens the realism of the configuration comparison. It allows the model to distinguish between new construction and existing infrastructure, interpret possible connections to the existing system, and assess whether proposed network layouts are consistent with the broader wastewater infrastructure context. This is particularly important in partially served districts, where future expansion must be coordinated with assets that are already operational.

2.6. Research Gap

The literature reviewed above provides useful foundations for wastewater infrastructure planning, but it does not fully resolve the type of problem faced in the Larnaka District. Wastewater system planning literature explains why spatial demand, settlement density, centralised and decentralised configurations, and governance capacity matter. Corridor-based and graph-based methods provide tools for representing connectivity and route alternatives. Optimisation literature provides concepts for shortest paths, tree structures, cost minimisation, and constrained network design. Hydraulic and pumping-station literature explains why terrain, gravity flow, and pumping requirements affect sewer feasibility. Brownfield infrastructure literature highlights the importance of existing assets for future planning.

However, these contributions are often developed separately. Centralised and decentralised wastewater studies often focus on system configuration at a conceptual or regional level. Spatial network studies provide methods for representing corridors and connectivity, but are not automatically wastewater-specific. Optimisation studies often address treatment technology, resource recovery, detailed pipe design, rehabilitation, or general network design rather than strategic sewer expansion in a partially served district. Pumping-station studies often focus on operation or detailed hydraulic design after the network layout is known. Brownfield infrastructure studies recognise the importance of existing assets, but do not by themselves provide a method for comparing new wastewater network configurations under budget and feasibility constraints.

The research gap is therefore not the absence of wastewater optimisation methods or hydraulic sewer design models. Rather, the gap is the limited availability of planning-level approaches that combine

spatially distributed wastewater demand, corridor-based graph representation, budget-constrained network expansion, existing sewer assets, municipal coverage objectives, and pumping-aware feasibility screening within a partially served district. This combination is required for the Larnaka case because the northern municipalities need a new wastewater system while the existing Meneou-based system remains operational in the southern part of the district.

The gap therefore motivates a spatial graph-based approach, since a graph is the natural structure in which spatially distributed demand, road-based construction corridors, existing assets, terrain, and treatment endpoints can be represented and compared within a single planning framework. This thesis addresses the gap by developing such an approach for wastewater network expansion in the Larnaka District. The approach links demand representation, corridor-based routing, non-budgeted and budgeted configuration generation, existing infrastructure interpretation, municipal-level coverage analysis, and pumping-related feasibility screening. Its contribution is not a final hydraulic design or a full treatment-plant site-suitability analysis, but a strategic decision-support framework for comparing technically plausible wastewater network configurations for Aradippou, Livadia, Pyla, Kellia, and Oroklini. The scientific contribution therefore lies less in any single component than in their integration: the value added is a transferable, planning-level framework that couples these previously separate strands, and that applies beyond Larnaka to other partially served districts facing budget-constrained sewer expansion under comparable spatial and regulatory conditions.

Table 2.1: Literature gaps and research needs for the Larnaka wastewater network planning case.

Limitation identified in the literature	Implication for the Larnaka case	Research need emerging from the gap
Wastewater system-configuration studies explain the relevance of centralised, decentralised, and hybrid systems [4], [12], [13], [14].	They clarify why density, distance, scale, and governance matter, but do not directly determine how the northern Larnaka municipalities should be connected through a collection network.	A planning approach is needed that translates spatial demand and service configuration into sewer network configurations for a defined service area.
Spatial network methods represent corridors and connectivity [16], [17], [18].	They provide useful graph representations, but do not automatically include wastewater demand, treatment endpoints, existing sewer assets, budget constraints, or pumping-related feasibility.	A wastewater-specific graph representation is needed to support corridor-based sewer network planning.
Graph algorithms and network design methods provide foundations for shortest paths, trees, and constrained connectivity [20], [21], [22], [23].	They support routing and cost-minimisation logic, but do not by themselves address municipal coverage, existing infrastructure context, or wastewater-specific feasibility constraints.	Graph-based heuristics must be adapted to wastewater planning objectives, including coverage, cost, municipal balance, and feasibility screening.
Hydraulic and pumping-station literature explains the role of gravity flow, slopes, pipe depth, and pumping infrastructure [5], [19], [25], [26].	Detailed hydraulic design or pump operation is usually addressed after a network layout is known, while strategic layouts may already imply major pumping needs.	Early-stage pumping-aware feasibility screening should be connected to spatial network configuration comparison.
Brownfield infrastructure literature recognises the importance of existing assets for future planning [5], [6], [19], [27].	The northern Larnaka system must be planned while the existing Meneou-based system remains operational in the southern part of the district.	Existing sewer assets should be represented and interpreted as part of the configuration comparison rather than treated only as background data.

3

Stakeholder Analysis and Current State of Larnaka

Before the research design is defined, this chapter establishes the real-world decision-making context that the modelling framework is intended to support. The stakeholder analysis centres on the District Local Government Organisation of Larnaka, as it was the only external organisation directly consulted during the research and the principal authority responsible for the wastewater-planning decisions considered in this thesis. The chapter first explains the role and responsibilities of the District Organisation and distinguishes it from other stakeholders that influence, finance, regulate, implement, or are affected by the proposed expansion. It then characterises the Larnaka wastewater case using publicly available information and evidence obtained through the stakeholder consultations. Finally, the resulting planning objective and stakeholder concerns are translated into the performance metrics that structure the research design developed in Chapter 4.

3.1. The District Local Government Organisation as Principal Stakeholder

This study was carried out in consultation with the District Local Government Organisation of Larnaka, which is treated throughout as the principal stakeholder and decision-maker. Understanding what this organisation is, and which responsibilities it holds, is a precondition for interpreting the planning objectives and performance metrics used in the remainder of the thesis.

The organisation is a product of the recent reform of local government in Cyprus. Under the District Local Government Organizations Law of 2022 (Law 37(I)/2022), five district-level organisations were established, one in each district of the government-controlled areas, and began operating on 1 July 2024 following the local government elections of June 2024 [28], [29]. Each organisation undertakes, within the boundaries of its district, four consolidated services: development licensing, water supply, sewage and stormwater drainage, and solid waste management. With their establishment, the former Water Supply Boards and Sewerage Boards were abolished and their competencies transferred to the new district organisations [29]. The District Local Government Organisation of Larnaka accordingly took over the services previously provided by the Larnaka Water Supply Board and the Larnaka Sewerage Board, and describes its mission in terms of local development with emphasis on water supply, sewerage, development licensing, and solid waste management [30].

This institutional context is what makes the organisation the principal stakeholder for the present study. Responsibility for planning and developing wastewater collection and treatment infrastructure across the Larnaka District now rests with a single district-level authority, rather than being divided among municipalities and a separate sewerage board. The District Organisation therefore represents the perspective from which the alternative wastewater expansion configurations are assessed and the actor ultimately responsible for balancing their competing objectives. Other organisations and groups

influence, finance, regulate, implement, or are affected by the decision, but they do not hold the same decision-making role within the scope of this research. These actors are described in Section 3.2.

The interaction with the District Organisation took place over two consultations, in April and June 2026, during the problem-framing and data-collection stages of the research. These consultations were used to clarify the geographical scope of the planning problem, including the broad area considered appropriate for the proposed northern treatment endpoint, the distinction between the existing southern system and the proposed northern system, the approximate investment range, the available wastewater-infrastructure information, and the planning outcomes considered relevant by the organisation. The stakeholder did not prescribe the optimisation algorithms, computational procedures, or modelling assumptions adopted in the thesis. These were developed by the researcher in order to translate the identified planning problem and stakeholder priorities into a reproducible analytical framework.

3.2. Broader Stakeholder Context

Although the District Organisation is the principal decision-maker and the only external organisation directly consulted during this research, the wastewater expansion decision also affects and is influenced by several other stakeholder groups. These actors are included to clarify the broader institutional, distributional, financial, and operational context within which the District Organisation must make its decision. Their interests were not elicited directly and are therefore inferred from their formal or functional role in the planning problem rather than presented as findings from the stakeholder consultations.

The northern municipalities and their residents are the principal beneficiaries of the proposed expansion. Their interest lies in gaining access to collective wastewater services and in avoiding a spatial distribution of investment that leaves particular municipalities or settlements persistently underserved. This interest is reflected in the population-coverage and municipal-distribution metrics.

European and national regulatory authorities form the regulatory context of the decision. Directive (EU) 2024/3019 establishes wastewater collection and treatment obligations at the level of individual agglomerations, making the distribution of coverage relevant in addition to district-wide performance. The municipal-coverage indicators therefore provide a planning-level indication of where further regulatory assessment may be required, without constituting a formal compliance evaluation.

The European Investment Bank and other public financing bodies represent the financial context of the expansion. Their interest lies in the credible and efficient allocation of infrastructure investment and in the financial feasibility of the proposed programme. These concerns are represented through total capital cost, cost per inhabitant served, and the comparison between full-coverage and budget-constrained configurations.

Finally, future designers, constructors, and operators of the wastewater system would be responsible for translating a selected planning direction into a hydraulically feasible and operational network. Their concerns include constructability, compatibility with existing assets, pumping requirements, energy use, maintenance, and treatment capacity. The present thesis addresses only the planning-level aspects of these concerns through the existing-infrastructure-integration and pumping-requirement metrics; detailed hydraulic and operational assessment remains outside its scope.

These stakeholders do not hold the same decision-making authority. Within the scope of this thesis, the District Organisation remains the actor responsible for weighing competing objectives and deciding which planning direction should be developed further. The broader stakeholder context nevertheless explains why the assessment cannot be limited to aggregate population coverage and cost, but must also consider municipal distribution, regulatory exposure, compatibility with existing infrastructure, and pumping-related consequences. The following section places these concerns within the specific wastewater-planning situation of the Larnaka District.

3.3. The Larnaka Case

The characterisation of the Larnaka case presented in this section draws on two types of source. Publicly available information is cited to its source where it is used. The remaining, case-specific information was obtained through stakeholder consultations carried out with the District Organisation during the thesis, conducted under an informed-consent procedure established for this purpose. In line with that

procedure, stakeholder input is reported in a general, de-identified form and is attributed to the organisation rather than to any individual. Unless a published source is cited, the description below reflects information provided during these consultations (District Local Government Organisation of Larnaka, personal communication, April and June 2026).

The wider study area comprises the municipalities of Larnaka, Aradippou, Livadia, Oroklini, Kellia, Dromolaxia–Meneou, Perivolia, Kiti, and Pyla, which together represent approximately $110\,000$ inhabitants and around $38\,000$ families. This population is distributed across dense urban cores, peri-urban settlements, and smaller communities, producing a heterogeneous spatial demand pattern for wastewater collection. Figure 3.1 provides a geographic overview of the study area and of the north–south distinction that structures the wastewater-planning problem discussed in the remainder of this chapter.

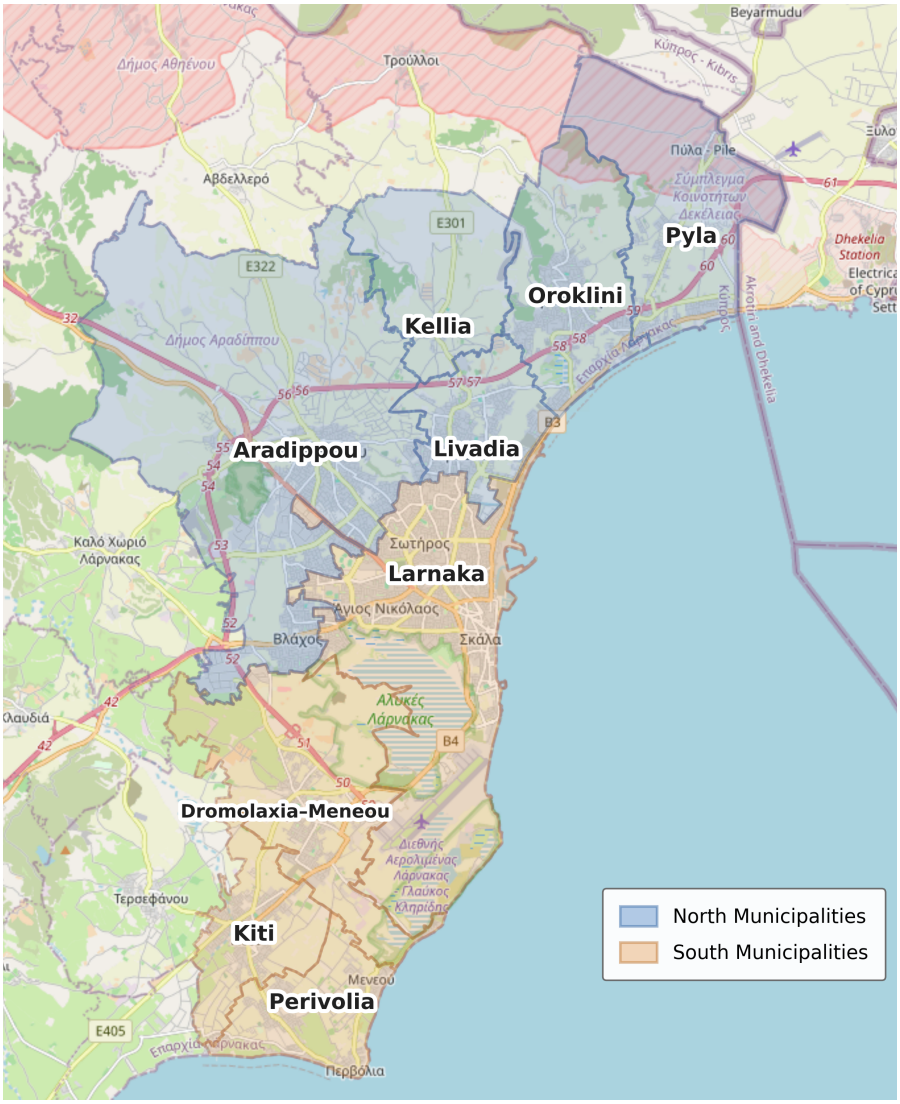


Figure 3.1: Overview of the Larnaka study area, distinguishing the northern municipalities considered for wastewater-network expansion from the southern municipalities associated with the existing service area.

The wastewater infrastructure of the district is unevenly developed. The southern part of the study area is already served, at least in its main urbanised areas, by the existing wastewater treatment plant located in the Meneou area, together with its associated sewerage network. This plant is a central asset of the current district system. It has a reported capacity of approximately $100\,000\,\mathrm{PE}$, expandable to $122\,000\,\mathrm{PE}$, currently treats roughly $18\,000\,\mathrm{m^3\,d^{-1}}$, and produces approximately $3.5\,\mathrm{million\,m^3}$ of reclaimed water annually, much of which is reused for agricultural irrigation [31], [32]. By contrast, the

northern and north-eastern part of the district remains unserved or only partially served by collective wastewater infrastructure. Approximately thirty surrounding communities still lack adequate sewerage, and a subset of these settlements exceeds $1000\,\mathrm{PE}$, placing them within the scope of the strengthened requirements of Directive (EU) 2024/3019 [7], [8].

For modelling purposes, the district is represented as a two-system configuration, a distinction established during the consultations. The existing southern wastewater system is referred to as WWTP1. It is associated with the Meneou treatment plant and with the already served or partially served southern municipalities, namely Larnaka, Dromolaxia–Meneou, Kiti, and Perivolia. The existing conduits and pumping stations in this part of the district are used as reference infrastructure layers for understanding the current system and its possible relationship with future expansion.

The proposed northern wastewater system is referred to as WWTP2. In the modelling workflow, WWTP2 does not represent a final, permitted treatment-plant location, but a planning-level northern treatment endpoint used to generate and compare sewer network expansion configurations. The northern system comprises the municipalities of Aradippou, Livadia, Pyla, Kellia, and Oroklini, which are treated as the primary service area for the proposed expansion.

The planning objective identified through the consultations with the District Organisation is to investigate how these five northern municipalities could be connected to a new wastewater treatment endpoint located in the northern part of the district. During the consultations, the organisation indicated that the planning-level search for this endpoint should focus on Kellia, Oroklini, and Aradippou. This indication defined a broad municipal search area rather than a specific, approved, or construction-ready treatment-plant location.

Ideally, the proposed network should provide full population coverage within the northern service area. Where full coverage is not achievable within the available financial constraints, the objective becomes to maximise the served population while maintaining a realistic network cost. The budget indicated by the organisation for the sewer-network component is approximately EUR 100–150 million, excluding the investment required for the construction of the new treatment plant itself.

The case is therefore treated as a budget-constrained network expansion problem, to be assessed not only in terms of spatial connectivity, but also in terms of population coverage, estimated pipe length, investment cost, municipal distribution, and likely pumping requirements. These assessment dimensions are formalised as performance metrics in Section 3.4. More broadly, the district is undergoing a significant wastewater investment programme, with the European Investment Bank committing EUR 230 million toward wastewater management and sewerage expansion across the district [9], which raises the importance of comparing expansion options carefully before committing resources.

A further planning question, also raised during the consultations, concerns the relationship between the existing southern system and the proposed northern system. Some existing or planned sewer sections currently associated with the southern system may need to be interpreted in relation to the future northern treatment endpoint. The thesis therefore considers whether selected parts of the available infrastructure appear more consistent with conveyance toward WWTP1 in Meneou or toward the proposed WWTP2 in the north.

Finally, two physical characteristics of the district, confirmed during the consultations, shape the feasibility of the northern system. First, much of the area is relatively flat and close to sea level, so that gravity-only conveyance may become difficult over long distances or across poorly graded routes, and combinations of gravity sewers, pumping stations, and pressure mains are likely to be required. Second, as part of the same consultations the organisation provided a partial representation of the existing wastewater infrastructure, comprising existing sewer conduits, supplied as georeferenced line geometries, and existing pumping stations, supplied as point locations.

These layers form the brownfield reference for the district. At this stage they are only introduced in order to establish what information the organisation contributed to the study. Their content, format, role in the model, quality, and limitations, together with the externally sourced datasets and the modelling assumptions, are presented in Chapter 5.

3.4. Planning Objectives and Performance Metrics

The overarching objective established in Section 3.3 is to connect the five northern municipalities to a new northern treatment endpoint, achieving full coverage where the available budget permits and otherwise maximising the served population at a realistic cost. Drawing primarily on the planning priorities identified during the consultations with the District Organisation, and informed by the broader stakeholder context described in Section 3.2, five performance dimensions were defined for comparing the alternative expansion configurations. These metrics do not replace the decision-maker's judgement, but make the principal trade-offs between service provision, affordability, distribution, infrastructure integration, and technical consequences explicit:

- **Population coverage.** The share of the northern demand connected by a configuration, evaluated both in aggregate and at municipal level, since the District Organisation must consider not only how many inhabitants are served but also how service is distributed.
- **Cost.** The estimated investment of a configuration, combining pipe construction and pumping-station capital expenditure, together with the resulting cost per inhabitant served, so that options can be compared against the available budget.
- **Municipal distribution.** The balance of service across the northern municipalities. This dimension has regulatory relevance because Directive (EU) 2024/3019 establishes obligations at the level of individual agglomerations rather than district-wide totals. Municipal coverage is used here as a planning-level distributional indicator and not as a formal assessment of regulatory compliance.
- **Integration with existing infrastructure.** The extent to which a configuration is interpreted coherently in relation to the existing brownfield assets and respects the functional distinction between the southern system, WWTP1, and the proposed northern system, WWTP2.
- **Pumping requirements.** The likely need for pumping infrastructure implied by a configuration, which in the flat terrain of the district affects cost, constructability, and operational complexity, and which must therefore be visible in the comparison rather than hidden behind pipe length alone.

Together, these five metrics translate the stakeholder-defined planning problem into a common basis for comparing alternative wastewater-network expansion configurations. They reflect the priorities identified through the consultations with the District Organisation while also capturing the principal regulatory, distributional, financial, and operational concerns associated with the broader stakeholder context.

Chapter 4 translates this decision context into the research objective, main research question, and sub-questions. The datasets, parameters, and assumptions required to represent the problem are documented in Chapter 5, after which Chapter 6 operationalises the five performance dimensions within the graph-based modelling workflow. The resulting configuration indicators are reported and compared in Chapter 7.

4

Research Design

This chapter translates the research gap identified in Chapter 2 and the performance metrics derived from the planning priorities identified during the stakeholder consultations in Chapter 3 into the research question structure that guides the thesis. Because the case, the actors, and the metrics they consider essential have already been characterised, the research questions can be defined so that they respond directly to those planning priorities. This chapter states the main research question, develops the related sub-questions, and explains how these questions organise the modelling workflow, from graph construction to network expansion, feasibility screening, and planning interpretation.

4.1. Research Objective and Main Research Question

The objective of this thesis is to develop a spatial graph-based approach to support wastewater network expansion planning in the northern part of the Larnaka District, for the municipalities of Aradippou, Livadia, Pyla, Kellia, and Oroklini, where a new collective wastewater network is required. In line with the planning priorities identified with the District Organisation in Chapter 3, the main planning objective is to maximise the population served by the new network, while the available budget of approximately EUR 100–150 million, the existing infrastructure context, and pumping feasibility act as the principal constraints on that objective. The aim is therefore to create a modelling framework that can represent the wastewater planning problem, generate alternative network expansion configurations, assess their technical plausibility, and compare them to support strategic planning recommendations.

Two clarifications define the scope of this objective. First, the research is positioned at planning level rather than final engineering design level: it does not aim to determine final pipe diameters, invert levels, pump capacities, or construction-ready layouts, but to provide a decision-support framework for comparing possible wastewater network configurations. Second, the intention is not to identify a single mathematically optimal network through exhaustive optimisation. Rather, it is to generate a small set of configurations under different, explicitly stated planning priorities and to make the trade-offs between coverage, cost, municipal distribution, integration with existing infrastructure, and pumping feasibility comparable, consistent with the performance metrics derived from the stakeholder consultations and defined in Section 3.4. The question of which configuration is preferable is therefore left to the decision-maker, informed by the comparison, rather than resolved by the model.

Based on this objective and on the research gap of Chapter 2, the main research question of this thesis is:

How can a spatial graph-based planning approach be used to generate, assess, and compare wastewater network expansion configurations that maximise population coverage for the northern part of the Larnaka District under budget, existing-infrastructure, and pumping-feasibility constraints?

4.2. Research Sub-Questions

The main research question is divided into five sub-questions. Each sub-question corresponds to one main step of the research workflow: graph construction, treatment-endpoint positioning, network expansion, feasibility screening, and configuration interpretation.

4.2.1. Sub-question 1: Baseline graph construction

SQ1. How can a baseline spatial graph be constructed to represent the wastewater network expansion problem in the northern Larnaka wastewater planning area?

The first sub-question concerns the creation of the graph on which the rest of the analysis is based. Here, the *baseline graph* is the spatial network of nodes and weighted edges that represents wastewater demand, feasible sewer corridors, existing wastewater infrastructure, treatment endpoints, and relevant topographic information, and that serves as the fixed modelling foundation on which all later steps operate. It therefore converts the spatial planning problem into a network structure that can be used for routing, expansion, cost estimation, and coverage analysis.

Answering this sub-question requires combining spatial datasets such as roads, buildings or population distribution, municipal boundaries, existing sewer assets, treatment infrastructure, and elevation data. The output is the baseline graph used as the modelling foundation for all later network expansion configurations.

4.2.2. Sub-question 2: Strategic treatment-endpoint positioning

SQ2. How can a planning-level treatment endpoint for the proposed northern wastewater system be selected and represented within the spatial graph?

The second sub-question concerns the positioning of the proposed northern wastewater treatment endpoint. Since all network expansion configurations start from this endpoint, its location influences pipe length, connection routes, cost, coverage, and pumping requirements. The objective is not to perform a complete WWTP site-suitability analysis, but to define a strategic graph-based endpoint that is consistent with the northern service area and can be used as the root of the network expansion algorithms.

Answering this sub-question requires a rule-based positioning approach. The requirements applied to the candidate endpoint follow from the northern service area and the planning priorities identified with the District Organisation in Chapter 3: the endpoint should remain spatially related to the main northern wastewater demand, avoid direct placement inside dense urban fabric where possible, and connect to the road-based graph used for routing. A single, best-scoring candidate is selected: the output is the one WWTP2 root node used by all subsequent network expansion configurations.

4.2.3. Sub-question 3: Network expansion algorithms

SQ3. How can graph-based algorithms be developed and applied to generate alternative wastewater network expansion configurations for the northern municipalities of the Larnaka District, including the allocation of existing sewer assets between the two treatment endpoints?

The third sub-question focuses on the development of the network expansion logic. Once the baseline graph and the treatment endpoint are defined, algorithms are needed to connect wastewater demand to the proposed northern WWTP through possible sewer corridors. These algorithms generate alternative layouts under different assumptions and planning priorities.

This step includes both non-budgeted and budget-constrained configurations. Non-budgeted configurations provide full-coverage reference networks, while budget-constrained configurations explore how the network could be expanded when financial resources are limited. Crucially, the budget-constrained configurations are not interchangeable: each operationalises a distinct stakeholder priority from Chapter 3, namely aggregate cost-efficiency, dense urban concentration, and balanced municipal distribution, so that every heuristic has an explicit objective aligned with one of the defined metrics. The step also reconsiders the existing sewer assets in relation to the two treatment endpoints, identifying which existing pipes are more coherently associated with the proposed northern system (WWTP2) rather than the existing southern one (WWTP1). The output is a set of alternative network configurations,

together with a planning-level interpretation of how existing infrastructure is integrated into the northern expansion context, that can be compared in terms of pipe length, cost, population coverage, municipal distribution, brownfield coherence, and spatial structure.

4.2.4. Sub-question 4: Pumping-feasibility screening

SQ4. How can pumping-related feasibility screening be used to identify where the generated wastewater network configurations are likely to require pumping, while incorporating the associated costs into the assessment of their technical plausibility?

The fourth sub-question addresses the fact that a spatially efficient network is not necessarily hydraulically plausible. In relatively flat areas, gravity-based sewer conveyance may become difficult, and some parts of the network may require pumping stations, pressure mains, or deeper excavation.

Because almost any layout can, in principle, be made to convey wastewater if enough pumping is added, the purpose of this step is not to test binary feasibility, nor to perform final hydraulic design. Instead, pumping-related feasibility screening identifies the sections of the generated network where terrain, slope, conveyance distance, or excessive required cover indicate probable pumping requirements, and hence how much pumping infrastructure a configuration implies. The associated capital cost is included in the cost metric defined in Section 3.4, so that the financial and technical consequences of pumping enter the comparison explicitly rather than remaining hidden behind pipe length. The output is a feasibility layer that supports interpretation of the technical plausibility and cost of the generated configurations.

4.2.5. Sub-question 5: Configuration comparison and planning recommendations

SQ5. How can the generated wastewater network configurations be compared to support planning recommendations for future sewer network expansion in the northern Larnaka District?

The fifth sub-question concerns the interpretation of the model results. Since each configuration reflects a different planning logic, the comparison must consider multiple dimensions rather than a single measure. To keep the assessment consistent, it uses the five performance metrics derived from the planning priorities identified during the stakeholder consultations and established in Section 3.4, namely population coverage, cost, municipal distribution, integration with existing infrastructure, and pumping requirements, rather than introducing a separate set of indicators here. Because these metrics were defined once on the basis of the planning priorities identified with the District Organisation, they are simply applied across all configurations at this stage.

Answering this sub-question allows the strengths, weaknesses, and trade-offs of each configuration to be identified. The final output is a set of planning recommendations indicating which network configurations appear most promising, which areas may require further technical investigation, and which uncertainties should be addressed before moving toward detailed engineering design.

4.3. Research Design Logic

The five sub-questions define a sequential workflow in which each step builds on the outputs of the preceding steps together with the fixed data, parameters, and modelling assumptions defined for the study. The baseline graph (SQ1) provides the modelling environment on which everything else operates, and the WWTP2 endpoint (SQ2) is fixed before any expansion is generated because it conditions the direction, length, and cost of every subsequent configuration. The expansion algorithms (SQ3) can therefore be applied to a stable problem definition, while the pumping-feasibility screening (SQ4) is deliberately placed after network generation: it is an interpretation layer that tests the technical plausibility of already-generated layouts rather than a constraint embedded in the routing itself. The configuration comparison (SQ5) finally integrates the quantitative indicators, the brownfield interpretation, and the feasibility screening into planning recommendations. The operational implementation of this sequence, including the inputs, outputs, and methods of each phase, is presented in Section 6.1.

5

Data and Modelling Assumptions

The modelling workflow developed in this thesis operates on a specific set of spatial and numerical data, which this chapter defines before the methodology is presented. Making the data explicit first is necessary because every subsequent modelling choice, and every limitation of the results, depends on what information was available, where it came from, and how it was made usable. The chapter is organised by provenance. It first describes the data received directly from the stakeholder, then the data obtained from external sources, distinguishing in each case the spatial datasets from the numeric parameters. It closes with the modelling assumptions adopted to bridge the remaining gaps.

5.1. Data Provided by the District Organisation

As established in Chapter 3, the case-specific information used in this study was provided by the District Local Government Organisation of Larnaka during the consultations of April and June 2026. This engagement supplied two kinds of information: the spatial datasets describing the existing wastewater infrastructure, and the numeric quantities defining the demand and the financial envelope of the problem.

5.1.1. Spatial Datasets

The District Organisation supplied a partial representation of the existing wastewater infrastructure of the district, shown in Figure 5.1. Two layers are central to the analysis. The first is the set of existing sewer conduits, provided as georeferenced line geometries with connectivity attributes describing how individual segments link together. The second is the set of existing pumping stations, provided as point locations; beyond their geometry, these points also carry a recorded maximum-depth attribute that is later used to calibrate the depth threshold of the pumping-feasibility screening (Section 6.5). The coverage of both layers is partial, concentrated in the areas visible in the figure rather than spanning the whole district, an aspect returned to in Assumptions A1 and A2. Despite this, the two layers form the brownfield reference for the district: they establish where wastewater infrastructure has already been constructed and provide the basis for later interpreting which existing sections relate more naturally to the southern endpoint (WWTP1) or to the proposed northern endpoint (WWTP2). Table 5.1 summarises these layers.

Table 5.1: Spatial datasets provided by the District Organisation.

Data layer	Format	Role in model
Existing conduits	Vector (lines)	Brownfield reference
Existing pumping stations	Vector (points)	Brownfield reference

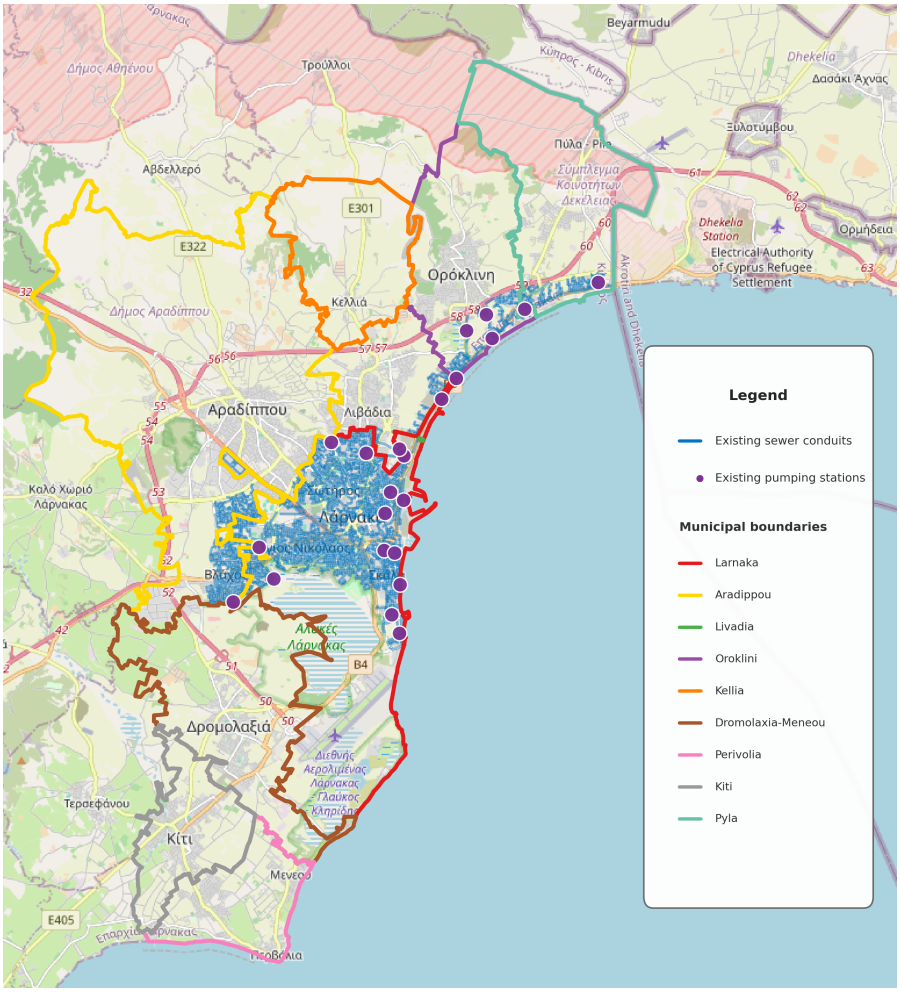


Figure 5.1: Existing wastewater infrastructure provided by the District Organisation: existing sewer conduits and existing pumping stations, shown against the municipal boundaries of the Larnaka study area.

5.1.2. Numeric Parameters

In addition to the infrastructure layers, the consultations with the District Organisation established the demand and financial quantities used to frame the problem. The wastewater generation rate of 120 litres per capita per day was agreed with the organisation and is consistent with typical domestic wastewater generation figures used in sewer planning; the unit capital cost of a new pumping station was likewise agreed with the organisation as a planning-level figure for the district. The indicative budget for the sewer-network component, excluding the treatment plant itself, was indicated by the organisation and is treated as the primary constraint in the budget-constrained configurations. These quantities are summarised in Table 5.2.

Table 5.2: Numeric parameters established through consultation with the District Organisation.

Parameter	Value
Wastewater generation rate	120 litres/capita/day
New pumping station capital cost	EUR 1.5 million per station
Sewer network budget	EUR 100–150 million (excludes treatment plant)

5.2. Externally Sourced Data

The remaining inputs were not part of the stakeholder hand-over and were obtained from open, published, or derived external sources. As in the previous section, the spatial datasets are described first and the numeric parameters second; because these inputs come from several different sources, the provenance is stated explicitly for each.

5.2.1. Spatial and Demographic Datasets

The road network and the municipal boundaries were both retrieved from OpenStreetMap. The drivable street network was obtained using OSMnx [16] and provides the set of constructible corridors for new sewers: because sewers are normally constructed along roads and public rights-of-way, the drivable road network is adopted as a planning-level representation of where new pipes can realistically be laid. The administrative boundaries of the nine municipalities were geocoded as polygons from OpenStreetMap via the same toolkit and define the service areas. Building footprints, used to distribute wastewater demand, were obtained from the Microsoft Global ML Building Footprints dataset, which provides polygon geometries of detected buildings derived from machine-learning extraction of satellite imagery [33]. Terrain elevation was obtained from the Copernicus DEM (GLO-30, 30 m resolution) [34] and is used in the pumping-feasibility screening. Finally, the municipal population basis was taken from the 2021 Census of Population and Housing [35] where available and from a secondary demographic source otherwise [36], as detailed in Assumption A4. All spatial layers were reprojected to a common projected coordinate system (EPSG:32636, UTM Zone 36N) so that lengths and distances are computed consistently in metres, and the municipal boundaries and population figures refer to the administrative configuration at the 2021 Census, prior to the 2024 local-government reform. Table 5.3 summarises these datasets and their sources. Figure 5.2 shows the main spatial inputs together.

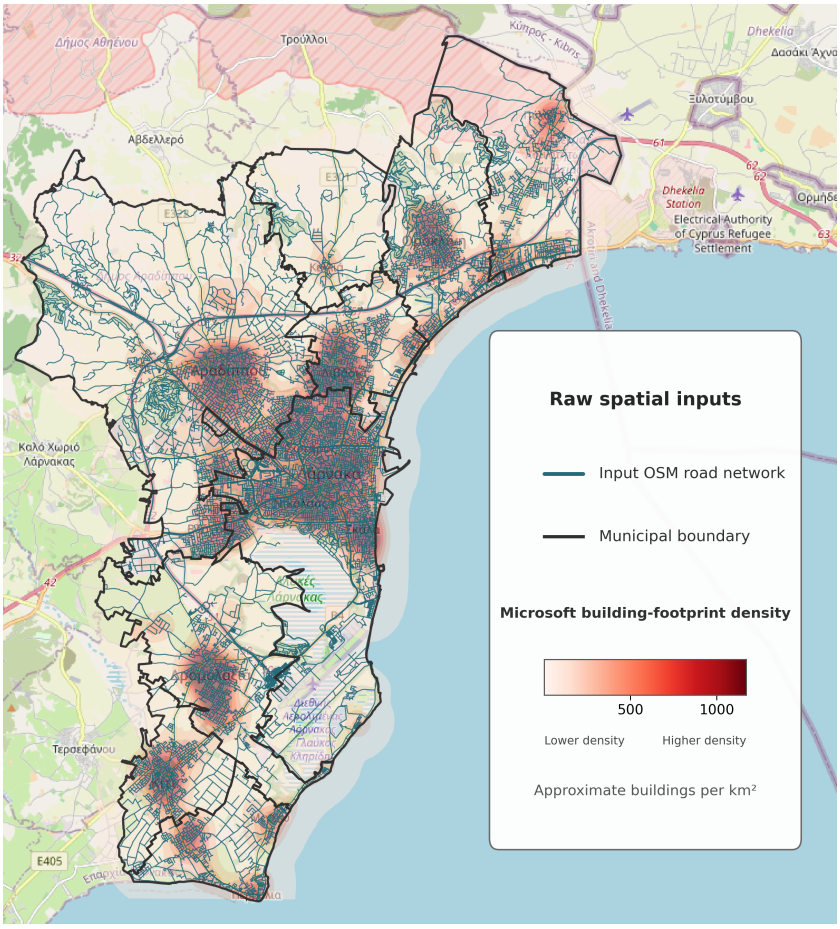


Figure 5.2: Externally sourced spatial inputs for the Larnaka planning case: the OpenStreetMap drivable road network, the municipal boundaries, and the density of the Microsoft building footprints.

Table 5.3: Externally sourced spatial and demographic datasets and their provenance.

Data layer	Source	Format	Role in model
Road network	OpenStreetMap	Vector (lines)	Corridor graph
Municipal boundaries	OpenStreetMap	Vector (polygons)	Service-area definition
Building footprints	Microsoft Global ML Building Footprints	Vector (polygons)	Demand disaggregation and urban-footprint delineation
Terrain elevation (DEM)	Copernicus DEM GLO-30	Raster (30 m)	Pumping screening
Population (municipal)	CYSTAT 2021 / Secondary (see A4)	Tabular	Demand distribution

The building footprints are further used to derive an *urban footprint*, a planning-level delineation of the main built-up areas that the expansion algorithms treat as the demand to be served. How this footprint is used within the modelling workflow is described in the methodology (Chapter 6), while the numeric thresholds that define it are listed, together with the other numeric parameters, in Section 5.2.2.

5.2.2. Adopted and Defined Numeric Parameters

Alongside the spatial datasets, a small set of numeric design, cost, and spatial parameters was adopted from the literature or defined for the modelling workflow. The pipe construction unit cost is a planning-level value adopted for this study; reported sewer construction unit costs vary widely with pipe diameter, trench depth, soil conditions, and terrain, and the adopted figure falls within the lower-to-middle range of published values [4], [5], [19]. The hydraulic parameters describe a single representative gravity sewer used only for the pumping-feasibility screening: a design diameter, a minimum self-cleansing velocity, a Manning roughness, the corresponding hydraulic radius, and a minimum soil cover. Adopting a single design pipe is consistent with the strategic scope of the study, in which individual pipe diameters are not yet determined.

Three additional distance parameters support the spatial integration and endpoint-positioning steps. Existing pumping stations are matched to a generated network within 500 m, so that only stations plausibly related to a configuration corridor are associated with it. For the positioning of WWTP2, candidate locations must remain at least 150 m outside the urban footprint, in order to avoid direct placement within dense built-up areas, and must lie within 400 m of a road-graph node, so that the selected endpoint can be represented within the routing graph. These values are planning-level spatial thresholds defined for this study; the full endpoint-screening procedure in which they are applied is described in Section 6.3. For the two cluster-based expansion heuristics, the urban terminal set is additionally partitioned using a regular 700 m grid. Candidate clusters are distinguished by grid cell, municipality, and connected road-graph component, as described in Section 6.4.3.

The maximum admissible gravity cover $\delta_{\max}$ is not adopted here but calibrated from the existing pumping-station data; that calibration is described in Section 6.5.

The numeric thresholds governing the urban footprint are also adopted at this stage. The footprint is obtained from the building layer through a buffer-based clustering rule: each building footprint is buffered by 80 m, overlapping buffers are dissolved into contiguous clusters, and a cluster is retained as urban only if it contains at least 20 buildings and has a total dissolved area of at least 25,000 m^2 (Table 5.4). The 80 m buffer links buildings close enough to share a local collection network without merging genuinely separate settlements, while the minimum building count and dissolved area discard small, scattered groups whose inclusion would require long, low-yield connections. The resulting urban footprint is a derived data layer, used by the methodology rather than produced as a result.

Table 5.4: Numeric parameters adopted or defined for the modelling workflow.

Parameter	Value	Basis
Pipe construction unit cost	EUR 400 per metre	Adopted [4], [5], [19]
Design pipe diameter d	300 mm	Adopted [5], [19]
Self-cleansing velocity v	0.60 m s^{-1}	Adopted [5], [19]
Manning roughness n	0.013	Adopted [5], [19]
Hydraulic radius $R = d/4$	0.075 m	Derived
Minimum soil cover	1.20 m	Adopted [5]
Existing pumping-station matching distance	500 m	Defined
WWTP2 minimum urban clearance	150 m	Defined
WWTP2 maximum snapping distance	400 m	Defined
Urban-footprint buffer	80 m	Defined
Urban-footprint minimum buildings	20	Defined
Urban-footprint minimum area	25,000 m^2	Defined
Urban-cluster grid size	700 m	Defined

5.3. Modelling Assumptions

The available data is not exhaustive, and the gaps are addressed through explicit modelling assumptions rather than treated as obstacles. Each assumption connects the available datasets and parameters to the modelling requirements and to what the District Organisation indicated during the consultations. The assumptions are stated here so that the configuration results in Chapter 7 can be interpreted against a clear set of boundary conditions.

A1 – Southern system treated as fully served context. The four southern municipalities (Larnaka, Dromolaxia–Meneou, Kiti, and Perivolia) are assumed to be entirely served by the existing WWTP1 system and are therefore treated as fully covered and excluded from the northern expansion analysis. Although excluded from the northern expansion objective, these municipalities remain within the wider study area because they define the spatial and infrastructure context of the existing WWTP1 system and support the interpretation of existing assets in relation to WWTP1 and WWTP2. This keeps the modelling focus on the five northern municipalities, consistent with the planning objective defined with the District Organisation. It is also a practical necessity, since the supplied data contains no conduit geometry for Kiti, Perivolia, and Dromolaxia–Meneou, so existing southern coverage cannot be represented explicitly. The assumption may slightly overstate southern coverage, as service is concentrated in the main urbanised cores rather than being universal, but it does not affect the northern results, which are the object of this study.

A2 – Partial pumping-station inventory. The pumping stations provided correspond only to the areas visible in Figure 5.1; stations elsewhere in the district are not included. The existing stations are therefore used as calibration evidence for the terrain–network contexts in which pumping has historically been required, not as a complete inventory.

A3 – Absence of hydraulic attributes and single design pipe. No pipe diameters, invert levels, or capacities were available for the existing network. Consistent with the planning-level scope, the analysis is restricted to spatial and screening-level reasoning: a single representative gravity sewer, defined by the parameters in Table 5.4, is assumed for the pumping-feasibility screening, and detailed hydraulic design is left to future work.

A4 – Demand distribution and population data. Municipal population is distributed to demand nodes within each municipality in proportion to the weighted area of the building footprints represented by each node, and converted to wastewater flow using the generation rate of 120 litres per capita per day reported in Table 5.2. Population figures for six of the nine municipalities (Larnaka, Aradippou, Livadia, Oroklini, Dromolaxia–Meneou, and Kiti) are taken from the 2021 Census of Population and Housing [35]. For the remaining three municipalities (Kellia, Pyla, and Perivolia), comparable 2021 census figures at municipal level were not retrievable, and population values were therefore taken from a secondary demographic source [36]. Since Kellia and Pyla fall within the northern service area, this introduces some uncertainty into their estimated demand; given their small populations relative to the northern total, the effect on the overall coverage results is limited.

A5 – Road network as construction corridor. New sewer pipes are assumed to be constructible along the drivable road network retrieved from OpenStreetMap. This reflects standard practice, in which sewers follow roads and public rights-of-way, and provides a realistic planning-level set of corridors. It excludes construction routes that do not follow the road network, such as pipes laid across open land, which is consistent with the strategic scope of the study.

A6 – Unit cost parameters. Construction cost is estimated using the unit pipe cost and the pumping-station capital cost. The pumping-station cost was agreed with the District Organisation, whereas the pipe unit cost is a planning-level value adopted for this study. Because the configuration cost estimates scale linearly with the pipe unit cost, it is the main source of cost uncertainty in the comparison and should be interpreted accordingly.

6

Methodology

This chapter explains how the data, parameters, and modelling assumptions defined in Chapter 5 are operationalised within the wastewater network expansion workflow. It presents the procedures used for graph construction, treatment-endpoint positioning, network expansion, brownfield reconciliation, pumping-feasibility screening, and configuration evaluation. The workflow follows the five sub-questions established in Chapter 4, while the performance dimensions applied in the final phase derive from Section 3.4. Results are reported in Chapter 7, and all mathematical notation is collected in the Nomenclature.

6.1. Research Framework and Model Integration

The methodology follows the five sequential phases introduced in Chapter 4. Together, these phases translate the spatial planning problem into a set of comparable wastewater network configurations. The sequence is designed so that each phase produces a clearly defined output that becomes an input to the subsequent phase, while the fixed datasets, parameters, and modelling assumptions established in Chapter 5 remain common across the entire workflow. This structure makes the modelling choices traceable and ensures that differences between configurations can be attributed to the methods used to generate and assess them rather than to changes in the underlying problem definition.

A graph-based representation is adopted because the planning problem combines several spatially referenced elements that must be analysed jointly. Wastewater demand is distributed across buildings and municipalities, new sewers must follow admissible construction corridors rather than straight-line connections, and several demand locations must be connected to the same treatment endpoint while allowing sections of pipe to be shared. The graph provides a common formal structure for these elements: demand is represented through node attributes, the road network defines candidate construction edges, existing conduits remain identifiable as brownfield assets, WWTP2 is represented as a root node, and terrain elevation is stored as a node attribute for the later pumping-feasibility screening.

The workflow begins with the construction of the baseline graph, which integrates the road network, spatial demand, existing wastewater infrastructure, and terrain information (Phase 1). A planning-level northern treatment endpoint is then selected and represented within the graph as the common root node used by all configurations (Phase 2). The baseline graph and root node form the fixed problem definition for the network-expansion phase, in which two non-budgeted and three budget-constrained heuristics generate alternative layouts under different routing and prioritisation logics (Phase 3). The generated layouts are also interpreted in relation to the existing brownfield infrastructure and the planning-level distinction between WWTP1 and WWTP2.

The resulting configurations are subsequently screened for likely pumping requirements using terrain, gravity-gradient, and excavation-depth information (Phase 4). This screening is deliberately applied after network generation rather than embedded directly in the routing algorithms. As a result, all configurations remain comparable in terms of the spatial logic that produced them, while their pumping implications are made explicit as a separate technical and financial consequence. Finally, the con-

figurations are evaluated using the common performance dimensions of population coverage, cost, municipal distribution, integration with existing infrastructure, and pumping requirements (Phase 5).

Figure 6.1 summarises the sequence and integration of the five phases, while Table 6.1 reports the corresponding inputs, outputs, methods, and research sub-questions.

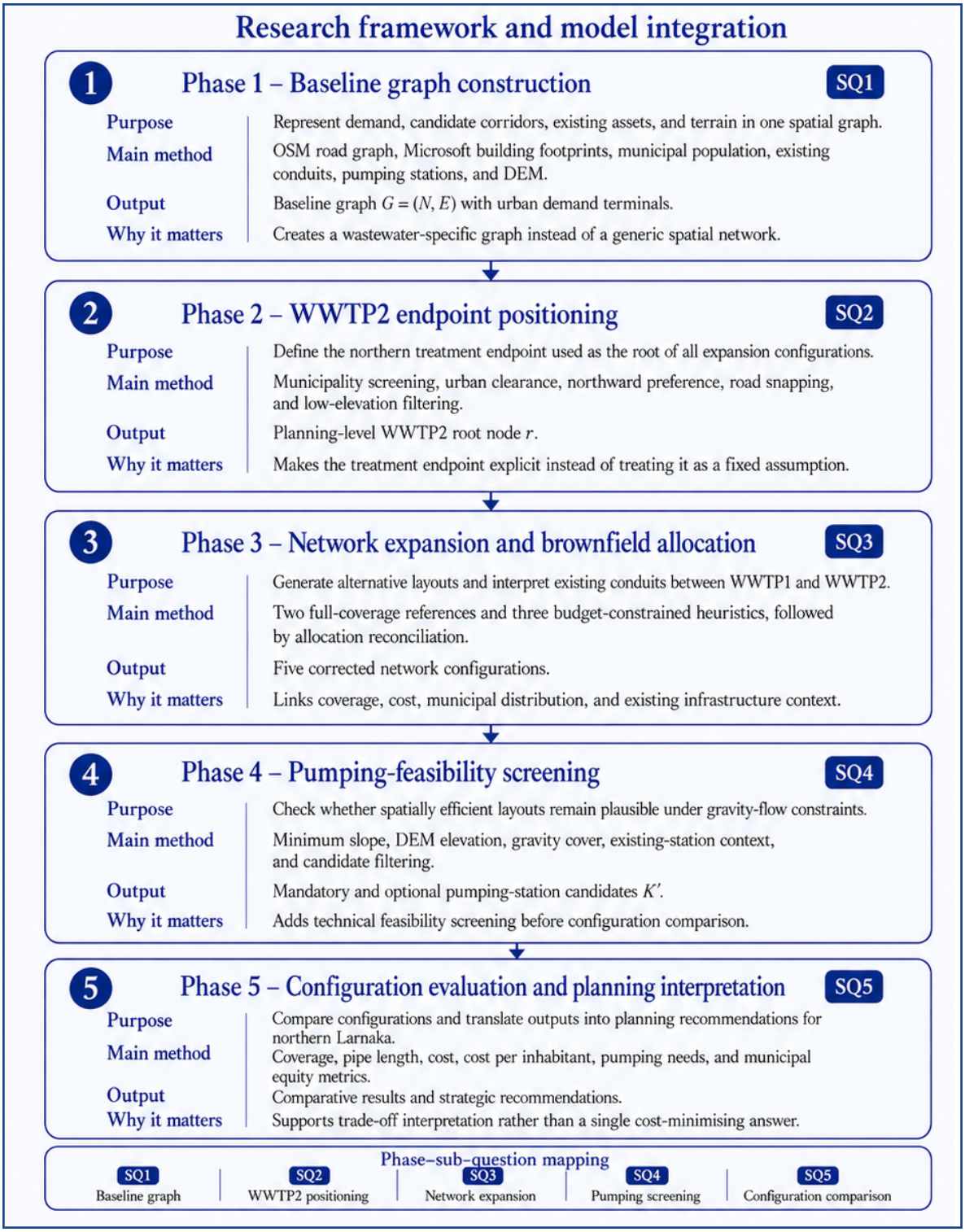


Figure 6.1: Overview of the research framework and model integration. Each phase transforms a defined input into a defined output that feeds the subsequent phase.

Table 6.1: Overview of the methodological phases, their inputs, outputs, main methods, and corresponding sub-questions.

Phase	Input	Output	Main method	SQ
1. Baseline graph construction	Spatial datasets and parameters of Chapter 5	Baseline graph $G = (N, E)$ with demand, corridors, existing assets, and node elevations	Graph construction, snapping, and demand assignment	SQ1
2. WWTP2 positioning	Graph G and endpoint-screening rules	Root node r connected to G	Rule-based positioning and scoring	SQ2
3. Network expansion and brownfield allocation	Graph G, root r, and budget β	Five network configurations and a planning-level WWTP1/WWTP2 allocation	Two non-budgeted heuristics, three budget-constrained heuristics, acyclicity verification, and reconciliation	SQ3
4. Pumping-feasibility screening	Five configurations and node elevations	Retained pumping-station set K' per configuration	Gravity-gradient and excavation-depth screening	SQ4
5. Configuration evaluation	Five configurations and pumping-feasibility layers	Comparable performance indicators	Metric computation	SQ5

6.2. Phase 1 -- Baseline Graph Construction

The first phase converts the spatial and demographic datasets defined in Chapter 5 into the baseline graph used by all subsequent phases. The road network provides the admissible construction corridors, the building and population datasets provide the spatial demand representation, the stakeholder-supplied conduits and pumping stations provide the brownfield reference, and the Copernicus DEM supplies the node elevations used later in the pumping-feasibility screening.

6.2.1. Graph formalism

The planning area is represented as an undirected weighted graph $G = (N, E)$, where N is the set of nodes and E is the set of edges. Each edge $e = (i, j) \in E$ carries a weight ℓ_e [m], equal to its metric length. The graph is undirected because flow direction is not imposed during routing; it is interpreted later through the terrain-based screening of Phase 4.

Nodes are distinguished by their role as road nodes, demand nodes $D \subseteq N$, existing-asset nodes, and the treatment endpoint $r \in N$ introduced in Phase 2. Edges are distinguished as existing conduits, candidate construction corridors, or connector edges. This classification allows new construction to be costed separately from the existing brownfield infrastructure.

All spatial layers use EPSG:32636, UTM Zone 36N, as defined in Section 5.2.1, so that distances, lengths, and areas are measured consistently in metres and square metres.

6.2.2. Road corridor graph

The corridor graph is constructed from the OpenStreetMap drivable road network described in Section 5.2.1. Road junctions become graph nodes and road segments become edges weighted by their metric length ℓ_e. Under Assumption A5, this network represents the admissible construction corridors for new sewers. Routes outside the road network, including direct connections across open land, are therefore not considered.

6.2.3. Demand representation

Municipal population must be converted into demand attached to the graph nodes on which the expansion algorithms operate. Let M be the set of municipalities, indexed by m, and let w_m [inhab.] be the population of municipality m. Let B_m be the set of building footprints within municipality m, and let a_b [m^2] be the footprint area of building b.

In accordance with Assumption A4, population is first distributed across the buildings of each municipality in proportion to building-footprint area:

$$p_b = w_m \frac{a_b}{\sum_{b' \in B_m} a_{b'}}, \qquad \forall b \in B_m,\ \forall m \in M, \tag{6.1}$$

where p_b [inhab.] is the population assigned to building b. This formulation preserves the municipal population total because summing p_b over all buildings in B_m returns w_m.

Each building is subsequently associated with its nearest road-graph node. Let B_i be the set of buildings assigned to node i. The population of demand node i is then

$$p_i = \sum_{b \in B_i} p_b, \qquad \forall i \in D, \tag{6.2}$$

where $D \subseteq N$ is the set of graph nodes receiving at least one building. A demand node may therefore represent one building or the combined population of several buildings assigned to the same road node.

The corresponding daily wastewater load is

$$f_i = \frac{p_i q}{1000}, \qquad \forall i \in D, \tag{6.3}$$

where $q = 120$ L capita^{-1} day^{-1} is the wastewater-generation rate reported in Table 5.2, and the factor 1000 converts litres to cubic metres. The routing algorithms use population p_i as their demand measure, while f_i is retained to express the represented demand in wastewater-flow units.

The expansion algorithms focus on the main built-up areas rather than on every isolated building. The urban footprint is derived using the thresholds defined in Section 5.2.2: building footprints are buffered by 80 m, overlapping buffers are dissolved, and a cluster is retained when it contains at least 20 buildings and has a dissolved area of at least 25,000 m^2.

Let

$$D^+ = \{i \in D \mid p_i > 0\} \tag{6.4}$$

be the positive-demand nodes, and define the terminal set as

$$T = \{i \in D^+ \mid i \text{ lies within the urban footprint}\}. \tag{6.5}$$

The set T is the demand target used by the expansion algorithms. Demand outside the urban footprint remains represented in D^+ but is not used to prioritise new construction. Consequently, the primary coverage metric refers to modelled urban population rather than to the complete administrative population. The difference is reported explicitly in Phase 5.

6.2.4. Integration of existing assets and terrain

The existing conduits and pumping stations described in Section 5.1.1 are incorporated as brownfield reference assets. Because the conduit geometries do not coincide exactly with the OpenStreetMap road graph, they cannot be assumed to be topologically connected to it. Existing conduit segments are represented as existing-conduit edges retaining their supplied geometry, while their endpoints are associated with nearby compatible road-graph nodes through short connector edges.

This operation preserves the location and identity of the supplied infrastructure while placing it within the same spatial structure used for the expansion analysis. It is a planning-level topological reconciliation and not a reconstruction of the hydraulic operation of the existing network.

Existing pumping stations are represented as point assets and matched to nearby graph nodes. Their recorded maximum-depth information is later used to calibrate the pumping-screening threshold, while their locations support the interpretation of pumping infrastructure in relation to WWTP1 and WWTP2.

Finally, each node $i \in N$ receives a ground elevation η_i [m a.s.l.] sampled from the Copernicus DEM described in Section 5.2.1. Elevation does not influence the network-generation heuristics and is used only in Phase 4.

6.3. Phase 2 -- WWTP2 Endpoint Positioning

All expansion configurations start from a single treatment endpoint, represented by the root node r. A single endpoint is used because the planning problem defined with the District Organisation concerns one new northern collective system complementing the existing southern system. Determining the number and location of multiple treatment plants would instead require a broader facility-location analysis including treatment capacities, land availability, siting constraints, and permitting, which lies outside the scope of this study.

The root is fixed before network generation because its position affects the routes, trunk length, construction cost, and pumping requirements of every configuration. Using the same root for all five configurations ensures that differences between them result from their routing and prioritisation logic rather than from different treatment locations.

The endpoint is selected through a rule-based screening that combines a stakeholder-informed municipal search area with fixed spatial parameters and additional methodological eligibility rules. As described in Section 3.3, the District Organisation indicated that the planning-level search for the proposed northern treatment endpoint should focus on Kellia, Oroklini, and Aradippou. These municipalities therefore define the admissible municipal search area. The fixed spatial parameters are the minimum clearance of 150 m from the urban footprint and the maximum snapping distance of 400 m to the road graph, both reported in Table 5.4. The northward preference, road-graph connectivity requirement, low-elevation filter, and final site-ranking rule were subsequently defined by the researcher to operationalise the stakeholder-provided spatial indication within the graph-based framework.

The screening proceeds through three successive steps. First, candidate locations are restricted to Kellia, Oroklini, and Aradippou, following the planning-level spatial indication provided by the District Organisation. These municipalities define the stakeholder-informed search area for WWTP2 while remaining spatially related to the wastewater demand of the five northern municipalities. Within this area, the population-weighted centroid of the northern urban demand is used as the principal demand reference point for the researcher-defined screening procedure.

Second, a geographic and planning filter is applied. Candidate locations must lie at least 150 m outside the urban footprint, avoiding direct placement within dense built-up fabric, and must satisfy a northward threshold beyond the main urbanised core and the S5–S6–S7 corridor. Where the road-reference information is insufficient, the northward threshold is determined using the northern distribution of demand and a minimum offset from the population-weighted centroid. Candidates must also belong to the relevant road-graph component and be located within 400 m of a road-graph node, ensuring that the selected endpoint can be represented within the graph used by the expansion algorithms.

Third, the Copernicus DEM is used to retain only candidates within the lowest 10th percentile of elevation among those satisfying the geographic filters. This constitutes a hard eligibility filter that removes comparatively high locations before the final ranking. Elevation is then considered a second time within the retained low-elevation subset through a normalised penalty in the site score. The two operations have distinct functions: the percentile filter restricts the comparison to relatively low candidate locations, while the penalty differentiates between the remaining candidates according to their relative elevation. Neither operation establishes hydraulic feasibility, but both favour a relatively low downstream treatment endpoint in the flat terrain of the district.

The candidates remaining after the geographic and elevation filters are ranked using the site score

$$s_j = d_j^{\mathrm{cent}} + 0.35\, d_j^{\mathrm{pref}} - 0.05\, \max(y_j - y_{\mathrm{north}}, 0) + \pi_j^{\mathrm{elev}}, \tag{6.6}$$

where s_j is the score of candidate j, d_j^{cent} [m] is its Euclidean distance from the population-weighted centroid of northern urban demand, and d_j^{pref} [m] is the absolute difference between its projected northing coordinate y_j and the preferred northing position:

$$d_j^{\mathrm{pref}} = |y_j - y_{\mathrm{pref}}| \,. \tag{6.7}$$

The elevation penalty is

$$\pi_j^{\mathrm{elev}} = 2000\, \widetilde{\eta}_j, \tag{6.8}$$

where $\widetilde{\eta}_j$ is the candidate elevation normalised between the 5th and 95th percentiles of elevation among the geographically feasible candidates:

$$\widetilde{\eta}_j = \mathrm{clip}\left(\frac{\eta_j - \eta_{0.05}}{\eta_{0.95} - \eta_{0.05}}, 0, 1 \right). \tag{6.9}$$

Here, η_j [m a.s.l.] is the ground elevation of candidate j, while $\eta_{0.05}$ and $\eta_{0.95}$ are respectively the 5th and 95th percentiles of elevation among the geographically feasible candidates. The factor 2000 m determines the maximum contribution of the elevation penalty to the site score. Values below the 5th percentile receive no elevation penalty, while values at or above the 95th percentile receive the maximum penalty.

The preferred northing y_{pref} is positioned 600 m north of the minimum admissible northing y_{north}. The first term of Equation (6.6) favours candidates close to the northern demand mass. The second term penalises departure from the preferred northing position, while the third provides a smaller additional reward for candidates located farther north than the minimum admissible threshold. The final term penalises comparatively high elevations within the already retained low-elevation subset. The coefficients 0.35 and 0.05 determine the relative strength of the two northward-position terms, while the 2000 m elevation weight controls the maximum influence of relative elevation.

Because lower scores indicate more favourable locations, the selected endpoint is

$$r = \arg\min_{j \in J^{\mathrm{feas}}} s_j, \tag{6.10}$$

where J^{feas} is the set of candidates satisfying the geographic, urban-clearance, road-connectivity, snapping-distance, and low-elevation requirements. Urban clearance and graph connectivity act as eligibility conditions and do not enter the score directly, whereas elevation influences the selection both through the initial lowest-decile filter and through the normalised penalty in Equation (6.8).

The resulting node r is used consistently across all five network configurations. It should be interpreted as a strategic treatment endpoint for configuration comparison, not as a permitted, hydraulically verified, or construction-ready wastewater treatment plant location. Table 6.2 summarises the complete screening sequence, the values applied, and the planning rationale associated with each criterion.

Table 6.2: Screening criteria used to position the WWTP2 root node r.

Criterion	Value or rule	Rationale
Admissible municipalities	Kellia, Oroklini, and Aradippou	Reflect the planning-level search area indicated during the stakeholder consultations and restrict the endpoint screening to municipalities spatially related to the northern service demand.
Demand reference point	Population-weighted centroid of northern urban demand	Keep the endpoint close to the principal demand mass and limit trunk distance.
Minimum clearance from urban footprint	150 m	Avoid placing the endpoint directly within dense built-up fabric.
Minimum northward position	Beyond the main urbanised core and the S5–S6–S7 corridor, with a demand-based fallback	Place the endpoint north of the coastal and central urban fabric associated with the existing southern system.
Preferred northing position	600 m north of the minimum admissible northing	Provide a reference position for ranking candidates that satisfy the minimum northward requirement.
Maximum snap distance to road node	400 m	Ensure that the endpoint can be represented within the road-based routing graph.
Graph-component eligibility	Relevant road-graph component	Ensure that the endpoint is reachable by the subsequent expansion algorithms.
Low-elevation eligibility	Lowest 10th percentile among geographically feasible candidates	Restrict the final ranking to relatively low candidate locations before the site score is applied.
Elevation penalty	Normalised between the 5th and 95th elevation percentiles and weighted by 2000 m	Differentiate the relative elevation of candidates remaining within the low-elevation subset.
Final candidate ranking	Minimum value of Equation (6.6)	Balance proximity to the demand centroid, preferred northward positioning, and relative elevation within the retained candidate subset.

6.4. Phase 3 -- Network Expansion and Brownfield Allocation

This phase connects the urban demand terminals T to the WWTP2 root r. The five resulting configurations are divided into two families.

The two non-budgeted configurations connect all terminals and provide reference layouts for the pipe length and cost required to serve the complete modelled urban demand. They are not presented as immediately financeable investment plans.

The three budget-constrained configurations apply the sewer-network budget and explore different ways of prioritising partial expansion. Shared-trunk emphasises aggregate population gain through reusable corridors, Urban-priority focuses on concentrated urban demand, and Municipality-targets promotes a more balanced distribution across the five northern municipalities.

6.4.1. Common formulation: cost model and selection rule

Let $E' \subseteq E$ be the set of candidate-corridor edges selected for new pipe construction. The total new-pipe length is

$$\ell(E') = \sum_{e \in E'} \ell_e,$$

where each edge is counted once, including when it is used by several connections. The corresponding pipe-construction cost is

$$C = c\,\ell(E') = c \sum_{e \in E'} \ell_e, \tag{6.11}$$

where $c = 400$ EUR m^{-1} is the unit pipe cost reported in Table 5.4. Existing conduits are not included in E' and therefore carry no new construction cost.

For the budget-constrained configurations, the budget β is converted into a maximum admissible new-pipe length:

$$\lambda_{\max} = \frac{\beta}{c}. \tag{6.12}$$

Using the lower bound of the stakeholder-defined envelope, $\beta = 100$ million EUR, gives $\lambda_{\max} = 250$ km. The lower bound is used because pumping-station requirements are not known during network generation; the remaining part of the EUR 100–150 million envelope therefore provides headroom for the pumping-station capital cost identified in Phase 4.

The budget-constrained heuristics build a configuration incrementally. For a candidate j, let ε_j be the new connecting edges and ρ_j the nodes on the corresponding connecting path. The marginal construction cost and benefit–cost score are

$$\Delta c_j = c \sum_{e \in \varepsilon_j} \ell_e, \qquad g_j = \frac{\Delta p_j}{\Delta c_j}, \tag{6.13}$$

where Δp_j is the additional population credited to candidate j. At each step, the selected candidate is

$$j^\star = \arg\max_j g_j \quad \text{subject to} \quad \ell(E') + \sum_{e \in \varepsilon_j} \ell_e \le \lambda_{\max}. \tag{6.14}$$

This is a greedy selection rule and does not guarantee a globally optimal network. Its role is to construct interpretable configurations under explicitly different planning priorities.

For Shared-trunk, the population gain is path-aware:

$$\Delta p_j = \sum_{i \in (\rho_j \cap T) \setminus S} p_i, \qquad \text{(path-aware)}, \tag{6.15}$$

where $S \subseteq T$ is the set of terminals already served. All unserved terminals encountered along the connecting path are therefore credited.

For Urban-priority and Municipality-targets, the gain is cluster-based:

$$\Delta p_j = \sum_{i \in \gamma_j \setminus S} p_i, \qquad \text{(cluster-based)}, \tag{6.16}$$

where $\gamma_j \subseteq T$ is the candidate urban cluster. Demand encountered incidentally along the connecting path does not influence the candidate ranking, although it is counted as served if it belongs to the final network.

6.4.2. Non-budgeted configurations: the cost of full urban coverage

The two non-budgeted heuristics connect every terminal in T to r. They represent contrasting full-coverage routing logics and make the effect of corridor sharing visible without constituting mathematical upper and lower bounds.

Rooted Dijkstra. A single-source Dijkstra search is performed from r over the weighted corridor graph. For every terminal $i \in T$, the shortest path from r to i is retrieved, and the configuration is formed by the union of those paths. Overlapping edges are included only once. The heuristic therefore provides a transparent full-coverage reference in which each terminal follows its individually shortest route and corridor sharing occurs only where shortest paths overlap naturally.

Prim–Steiner heuristic. The Prim–Steiner heuristic begins with a tree containing only r. At each iteration, it identifies the unconnected terminal nearest to the existing tree and adds its shortest connecting path. Each new terminal therefore attaches to an existing branch rather than being routed independently to the root. The procedure continues until all terminals are connected and provides a computationally tractable Steiner-type approximation that explicitly encourages shared trunks. Figure 6.2 illustrates how the second connection differs between the Rooted Dijkstra and Prim–Steiner logics.

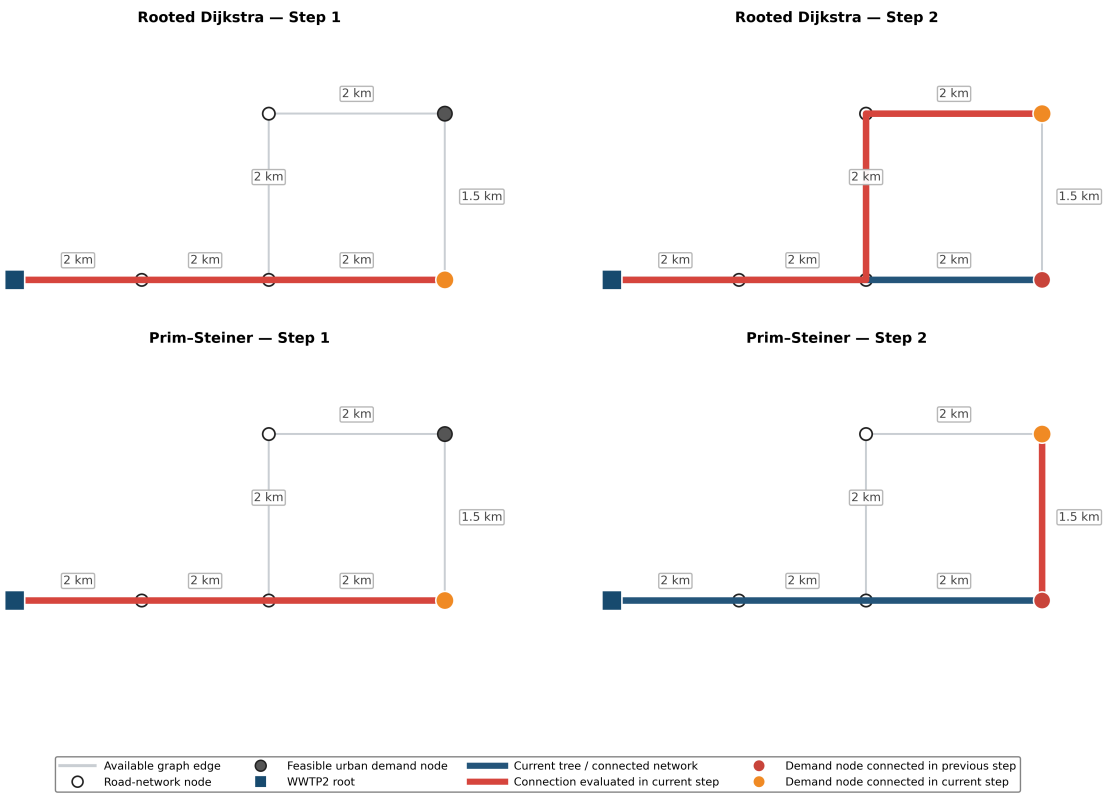


Figure 6.2: Schematic comparison of the Rooted Dijkstra and Prim–Steiner connection logics. Rooted Dijkstra connects each terminal through its shortest route from the endpoint, whereas Prim–Steiner attaches each new terminal to the network already constructed.

6.4.3. Budget-constrained configurations: coverage under limited funding

The budget-constrained configurations share the length ceiling $\lambda_{\max}$ and the greedy score of Equation (6.13), but use different candidate units and definitions of population gain.

Shared-trunk heuristic. Each candidate is an unserved terminal and is evaluated using the path-aware gain of Equation (6.15). The heuristic selects the connection providing the greatest additional population per unit of marginal cost, including demand encountered along the route. It therefore rewards extensions that create shared trunks and collect several demand nodes along the same corridor. Figure 6.3 illustrates how demand encountered along a candidate path contributes to its ranking.

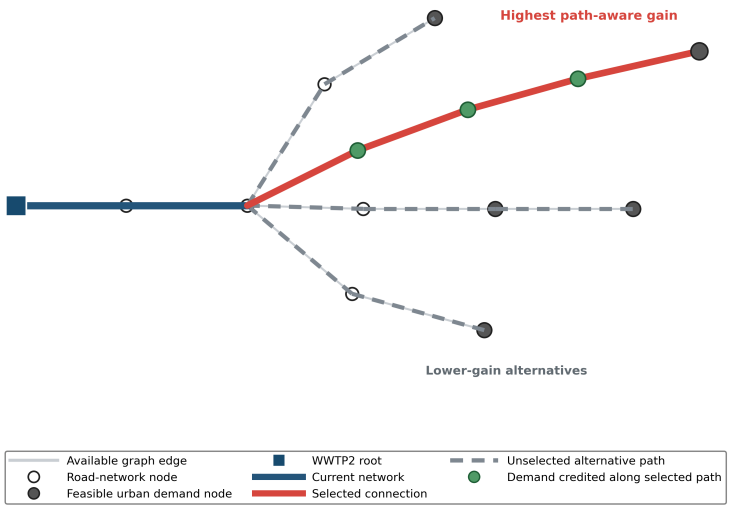


Figure 6.3: Selection logic of the Shared-trunk heuristic. Candidate connections are ranked by the unserved demand collected along the connecting path relative to the additional pipe cost.

Urban-priority heuristic. Each candidate is an urban cluster derived from the urban-demand representation. Candidates are evaluated using the cluster-based gain of Equation (6.16). The score therefore reflects the population of the selected cluster relative to the cost of connecting it and excludes incidental demand along the connecting route.

Candidate urban clusters are constructed using the 700 m grid reported in Table 5.4. Each cluster contains terminals located in the same grid cell, municipality, and connected road-graph component. Separating clusters by municipality preserves municipal attribution, while separating them by graph component prevents disconnected terminals from being treated as one connectable candidate.

This distinction prevents Urban-priority from reproducing the Shared-trunk logic. It prioritises cost-efficient connections to concentrated urban demand, but does not necessarily select the largest cluster in absolute terms: a smaller nearby cluster may rank above a larger and more distant cluster. Figure 6.4 illustrates the cluster-based selection rule and its exclusion of incidental path demand.

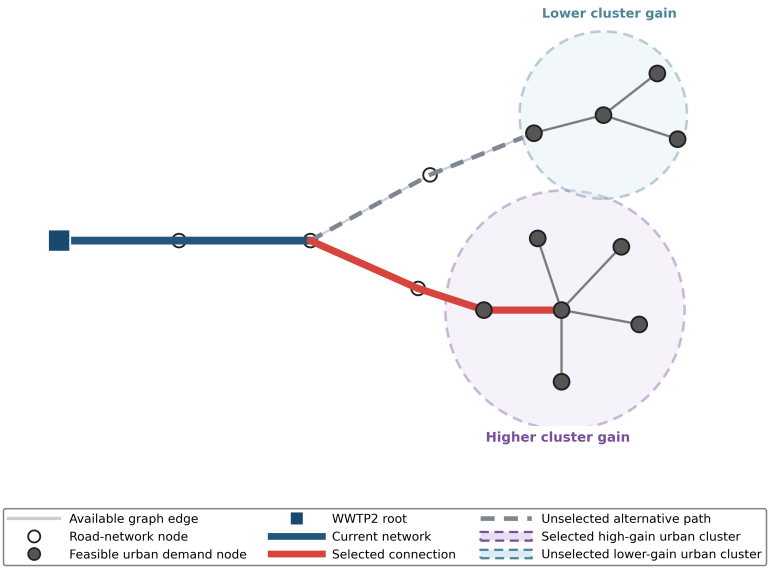


Figure 6.4: Selection logic of the Urban-priority heuristic. Candidate urban clusters are ranked by their own population relative to their connection cost; demand located along the connecting path does not enter the selection score.

Municipality-targets heuristic. Municipality-targets uses the same urban-cluster candidates and cluster-based score as Urban-priority, but restricts which municipalities are eligible at each stage. Expansion proceeds through municipal coverage targets of 30%, 50%, and 70%.

During each stage, only clusters located in municipalities whose current coverage remains below the active target are eligible. Among those clusters, the algorithm selects the one with the highest benefit–cost score. When all municipalities reach the current target, or when no further eligible cluster can be added within the remaining budget, the next target becomes active.

After the 70% stage is completed or exhausted, any remaining budget is allocated through a residual phase using the same cluster-based score without a municipal eligibility restriction. The staged procedure ensures that a basic level of service is pursued across all five municipalities before investment becomes concentrated in the most efficient locations. Figure 6.5 illustrates the eligibility check applied before candidate clusters are ranked.

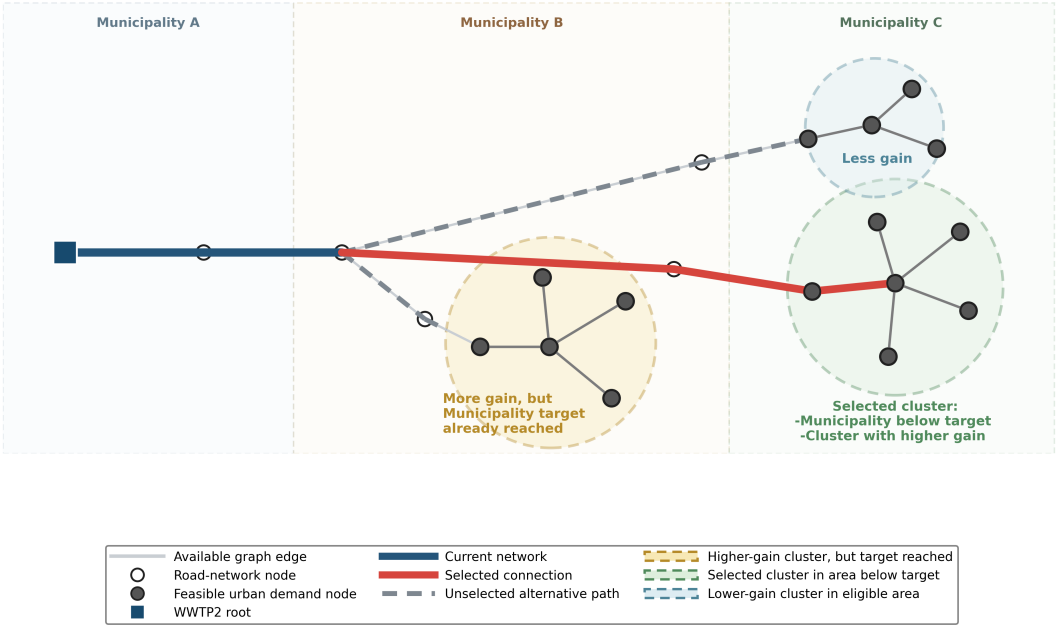


Figure 6.5: Selection logic of the Municipality-targets heuristic. Municipal eligibility is evaluated before candidate clusters are ranked, preventing municipalities already above the active target from receiving additional investment during that stage.

Table 6.3: Characteristics of the five network expansion heuristics.

Heuristic	Selection logic	Path-aware	Budgeted
Rooted Dijkstra	Union of shortest paths from r to each urban terminal	—	No
Prim–Steiner	Grow a tree by attaching the nearest unconnected urban terminal	—	No
Shared-trunk	Maximise g_j using demand along the connecting path	Yes	Yes
Urban-priority	Maximise g_j using the population of the selected urban cluster	No	Yes
Municipality-targets	Apply staged municipal targets of 30%, 50%, and 70%, followed by residual allocation	No	Yes

6.4.4. Acyclicity of the generated layouts

Acyclicity is required because a gravity-sewer layout should provide each connected node with a unique downstream route and should not contain redundant closed loops. The five heuristics are therefore

implemented so that acyclicity is obtained by construction rather than through the removal of surplus edges after network generation.

For Rooted Dijkstra, all terminal paths are retrieved from one single-source Dijkstra search rooted at r. Each reachable node is assigned one predecessor, and equal-length alternatives are resolved once within the same predecessor structure. The union of the terminal paths is therefore a subtree of this single-source structure rather than the union of independently computed paths. Deduplicating repeated corridor records changes only how pipe length and cost are counted and does not alter this topology.

Prim–Steiner and Shared-trunk grow one common structure from the root. At each iteration, a multi-source shortest-path search connects an unserved terminal to the network already constructed. The added path meets the existing network at one attachment point; adding such a branch to an acyclic structure cannot create a cycle. In Prim–Steiner, the same tree is carried across the five municipalities rather than being restarted independently for each one.

Urban-priority and Municipality-targets apply the same principle to cluster-based candidates. Once a cluster has been selected, its internal connection is reconstructed from the network as it exists at that iteration. Its terminals are attached incrementally through multi-source shortest paths rather than through a local tree precalculated independently of the current network. This prevents a cluster tree from intersecting the existing layout at a second point and closing a loop.

The property is verified numerically for each completed configuration using the cyclomatic number

$$\mu = |E'| - |N'| + \kappa,$$

where E' is the set of selected new-pipe edges, N' is the set of nodes incident to those edges, and κ is the number of connected components. A value $\mu = 0$ confirms that the selected layout is acyclic. The verification additionally checks that the relevant component contains r, that no selected corridor is recorded more than once, and that every served terminal has a path to the root.

6.4.5. Network reconciliation and WWTP1/WWTP2 allocation

After generation, the five configurations are interpreted in relation to the existing sewer infrastructure. This step considers how the relevant existing conduits could be associated with the southern system, WWTP1, or the proposed northern system, WWTP2.

The procedure is a strategic spatial allocation rather than a hydraulic reassignment. The supplied conduits lack flow directions, invert levels, capacities, and operational information, so the analysis cannot determine how wastewater would physically be redirected between treatment systems.

The allocation proceeds in three steps. First, existing conduits located in the northern municipalities are assigned to WWTP2, while conduits in the southern municipalities remain associated with WWTP1. Second, the transition area is refined by considering conduits near the boundary between the two systems, avoiding a classification based solely on administrative borders. Existing conduits are progressively transferred toward WWTP2 until the population associated with the northern allocation reaches approximately 40% of the population represented in the allocation.

Third, the automatic result is reviewed manually to remove short isolated conduit sections that remain assigned to one system while being surrounded by conduits assigned to the other. These fragments arise from split geometries, boundary effects, and local snapping mismatches. The review improves spatial coherence and moves the final allocation toward an approximately balanced WWTP1/WWTP2 division.

The 40% automatic target and the approximately balanced final split are modelling assumptions made by the researcher. They were not prescribed by the District Organisation and are not derived hydraulically. Their role is to operationalise the two-system interpretation established during the consultations while leaving room for the manual correction step.

Reallocating an existing conduit does not add new pipe and therefore does not enter the construction cost of Equation (6.11). In practice, connecting works or lifting infrastructure could be required to redi-

rect wastewater between systems, but these costs cannot be estimated from the available hydraulic data.

The output of Phase 3 is a new-pipe layout for each heuristic, together with a planning-level allocation of relevant existing assets between WWTP1 and WWTP2.

6.5. Phase 4 -- Pumping-Feasibility Screening

A spatially efficient configuration may still require excessive excavation to maintain gravity flow. Phase 4 screens each generated layout to identify where pumping is likely to be required. The procedure is not a final hydraulic design: it does not size pumps, wet wells, or pressure mains, but estimates the number and location of probable pumping stations and incorporates their capital cost into the comparison.

6.5.1. Hydraulic design basis

The screening adopts the representative gravity-sewer parameters reported in Table 5.4: a diameter $d = 300$ mm, self-cleansing velocity $v = 0.60$ m s^{-1}, Manning roughness $n = 0.013$, hydraulic radius $R = d/4 = 0.075$ m, and minimum soil cover of 1.20 m. Existing pumping stations are matched to configuration networks within the 500 m distance defined in the same table.

A single representative sewer is used because individual pipe diameters and design flows are not determined at this planning stage. The resulting screening provides a consistent comparison across configurations rather than a construction-ready hydraulic profile.

6.5.2. Gravity gradient and excavation depth

The minimum gravity slope corresponding to the adopted self-cleansing velocity is calculated using Manning's equation:

$$s_{\min} = \left(\frac{vn}{R^{2/3}} \right)^2 . \tag{6.17}$$

Ground elevations are sampled from the Copernicus DEM and locally smoothed to reduce raster-scale noise. Starting from the upstream branches and proceeding toward r, a required invert profile is constructed so that the pipe falls by at least $s_{\min}$ while maintaining the minimum cover.

The required excavation depth at node i is

$$\delta_i = \eta_i - I_i, \tag{6.18}$$

where η_i is the DEM-derived ground elevation and I_i is the required invert elevation. Where the terrain falls more slowly than the required pipe gradient, the required depth accumulates along the route. Long flat sections and adverse gradients therefore produce larger values of δ_i.

When a pumping station is introduced, the profile is reset and a new gravity reach begins. This represents the assumption that pumping restores a workable downstream invert level; the required lift height and pressure-main design are not calculated.

6.5.3. Classification of pumping requirements

The maximum admissible gravity cover $\delta_{\max}$ is calibrated from the available `MaxDepth` values of the existing pumping stations. The 90th percentile is 8.63 m, above the adopted minimum floor of 8 m, and therefore

$$\delta_{\max} = 8.63 \text{ m}. \tag{6.19}$$

This locally calibrated value is applied consistently across all five configurations. It is a screening threshold rather than a design standard.

Candidate identification, classification, and retention are separate steps. A raw candidate is first generated when the required depth exceeds $\delta_{\max}$ by at least 1.75 m. Consecutive raw candidates on the

same branch must be separated by at least 800 m of network distance, after which candidates are spatially deduplicated using a minimum Euclidean separation of 1000 m.

The filtered candidates are then classified as mandatory, optional, or screened out. A high-depth always-keep trigger retains any candidate with a depth excess of at least 5.0 m. The implementation also records a severe-depth condition at 7.0 m, but this does not create an additional retention threshold because the 5.0 m always-keep rule has already been activated. Other mandatory conditions concern substantial adverse rise over a long upstream branch and contexts resembling those of the existing pumping stations. Optional candidates require a depth excess of at least 2.75 m together with at least 1200 m of upstream network length and must not satisfy a mandatory condition. Table 6.4 distinguishes these rules from the earlier 1.75 m raw-candidate detection threshold.

Table 6.4: Detection, classification, and treatment of pumping-station candidates. The 1.75 m threshold identifies raw candidates; it is not the optional-retention rule.

Stage or category	Trigger condition	Treatment
Raw candidate	Required-depth excess above $\delta_{\max}$ of at least 1.75 m	Passed to network-spacing and spatial-deduplication checks
Mandatory	Any mandatory trigger, including the 5.0 m high-depth always-keep rule, a substantial adverse rise combined with a long upstream branch, or an existing-pumping-station-like context. A 7.0 m severe-depth flag is also recorded but is already covered by the 5.0 m always-keep rule	Always retained
Optional	Depth excess of at least 2.75 m, upstream network length of at least 1200 m, and no mandatory trigger	Ranked and retained subject to the configuration-family cap
Screened out	Candidate removed by spacing or deduplication, or not satisfying the mandatory or optional retention rules	Discarded

Optional candidates are ranked by depth exceedance and affected upstream network length. For configuration family f, the maximum retained optional count is

$$K^{\mathrm{opt}}_{\max,f} = \min\left(\lceil \phi_f \, |K^{\mathrm{ex}}| \rceil \, , K^{\mathrm{abs}}_f\right), \tag{6.20}$$

where K^{ex} is the set of existing pumping stations. The non-budgeted family uses $\phi_f = 0.75$ and $K^{\mathrm{abs}}_f = 30$, while the budget-constrained family uses $\phi_f = 0.35$ and $K^{\mathrm{abs}}_f = 15$. With the 22 existing stations available in the Larnaka dataset, these rules produce effective optional caps of 17 and 8, respectively; the absolute ceilings of 30 and 15 are therefore not binding in this case. Mandatory candidates are not removed by these caps.

Existing stations are matched to each configuration within 500 m and used as local empirical evidence for screening and for interpreting their relationship with WWTP1 and WWTP2. The output is the retained set K', reported separately as mandatory and optional stations.

6.6. Phase 5 -- Evaluation Metrics

The final phase operationalises the five performance dimensions established in Section 3.4: population coverage, cost, municipal distribution, integration with existing infrastructure, and pumping requirements.

Urban population coverage. The primary coverage metric is the percentage of modelled urban population connected by a configuration:

$$x_u = \frac{\sum_{i \in S} p_i}{\sum_{i \in T} p_i} \times 100, \tag{6.21}$$

where T is the terminal set and $S \subseteq T$ is the subset belonging to the configuration. A terminal located on a selected path is counted as served even when the path was originally selected to reach another candidate.

Total-population coverage. A contextual coverage metric is computed over all positive-demand nodes:

$$x_{\text{tot}} = \frac{\sum_{i \in S_{\text{tot}}} p_i}{\sum_{i \in D^+} p_i} \times 100, \tag{6.22}$$

where $S_{\text{tot}} \subseteq D^+$ is the set of positive-demand nodes treated as served in the final configuration interpretation. It includes the positive-demand nodes belonging to the selected network and the demand assigned to the existing brownfield service context. Under Assumption A1, the positive-demand nodes in the four southern municipalities are therefore included as served by WWTP1, while northern positive-demand nodes are included when they are connected through the generated WWTP2 network or incorporated into the reconciled existing-infrastructure allocation. Positive-demand nodes outside these served network and brownfield components remain unserved.

This metric is not an optimisation target. It provides a district-wide contextual measure that includes both urban and non-urban positive demand, whereas x_u evaluates only the modelled urban terminal set T used by the expansion algorithms.

Municipal coverage. For municipality m, urban population coverage is

$$x_m = \frac{\sum_{i \in S \cap T_m} p_i}{\sum_{i \in T_m} p_i} \times 100, \qquad \forall m \in M, \tag{6.23}$$

where $T_m \subseteq T$ is the set of urban terminals located in municipality m. The municipal values allow configurations with similar aggregate coverage but different spatial distributions to be distinguished.

Municipal balance is additionally summarised using the standard deviation of coverage across the five northern municipalities:

$$\sigma_x = \sqrt{\frac{1}{|M^{\text{N}}|} \sum_{m \in M^{\text{N}}} (x_m - \bar{x})^2},$$

where M^{N} is the set of northern municipalities and $\bar{x}$ is their unweighted mean coverage. A lower σ_x indicates a more even municipal distribution. The minimum municipal coverage,

$$x^{\min} = \min_{m \in M^{\text{N}}} x_m,$$

is also reported to identify the least-served municipality.

Cost. The total capital cost combines new pipe construction and retained pumping stations:

$$z = c\,\ell(E') + h\,|K'|, \tag{6.24}$$

where $h = 1.5$ million EUR per station is reported in Table 5.2. Existing conduits and existing pumping stations are not charged as new capital expenditure. Operating and maintenance costs are outside the scope of the model.

The cost per inhabitant served is

$$u = \frac{z}{\sum_{i \in S} p_i}. \tag{6.25}$$

Existing-infrastructure integration and pumping requirements. Integration with existing infrastructure is assessed through the planning-level allocation of existing conduits and pumping stations between WWTP1 and WWTP2, together with the spatial coherence of the final brownfield reconciliation. This dimension therefore evaluates whether each configuration is interpreted consistently within the existing two-system context, rather than measuring the hydraulic utilisation, residual capacity, or operational performance of the supplied assets. Pumping requirements are reported through the retained set K', separated into mandatory and optional stations. Together with new-pipe length, population coverage, municipal distribution, total cost, and cost per inhabitant served, these indicators form the basis of the configuration comparison in Chapter 7.

6.7. Verification and Validation

Verification checks whether each computational step produces internally consistent outputs. Phase 1 checks confirm that municipal population is conserved by Equation 6.1, that buildings and existing assets are assigned to the graph, and that the spatial layers use the correct coordinate reference system. Phase 2 checks that r satisfies the endpoint-screening rules and is connected to the relevant corridor-graph component. Phase 3 checks that the budget-constrained configurations respect $\lambda_{\max}$, that the selected new-pipe layouts are acyclic, and that the brownfield allocation contains no isolated contradictory fragments. Phase 4 checks the availability of node elevations and the consistent application of the gravity-gradient and pumping-classification rules.

Validation is necessarily partial because no constructed northern wastewater network exists against which the configurations can be compared. The existing pumping-station dataset provides local empirical calibration and a limited plausibility check for the pumping-feasibility screening. Its recorded depth values are used to calibrate $\delta_{\max}$, while the terrain contexts surrounding existing stations support the interpretation of new candidates. Because the same evidence contributes to both parameterisation and subsequent comparison, this should not be interpreted as independent validation. The procedure provides local grounding for the screening but does not validate pipe capacities, invert levels, flow directions, pump sizes, or treatment capacity.

The complete verification and validation checks and their quantitative outcomes are reported in Appendix C.

7

Results

This chapter presents the spatial and quantitative results of the modelling workflow developed in Chapter 6. The chapter follows the same five-phase structure used in the methodology, so that each results section corresponds to one research sub-question: baseline graph construction, WWTP2 endpoint positioning, network expansion and brownfield allocation, pumping-feasibility screening, and final configuration comparison. All monetary results use the unit costs reported in Tables 5.2 and 5.4.

7.1. Phase 1 Results -- Baseline Graph, Demand Representation, and Initial Coverage

The baseline graph construction of Phase 1 distributes the municipal population across building footprints and aggregates it to road nodes. This produces a set of positive-population demand nodes D^+ and, after urban-footprint filtering, the modelled urban terminal set T. Table 7.1 reports the total positive population and the modelled urban population by municipality.

The modelled urban population is $109{,}129$ inhabitants, compared with a total positive population of $110{,}260$ inhabitants. The excluded non-urban demand is therefore $1{,}131$ inhabitants, equal to 1.0% of the total positive population. This small difference explains why the contextual total-population coverage x_{tot} remains close to the primary urban coverage metric x_u throughout the results. Nevertheless, x_u remains the main performance metric because the expansion algorithms are applied to the urban terminal set T.

Table 7.1: Total positive population P_m^+ and modelled urban population P_m^u by municipality. The excluded non-urban share is the demand outside the urban footprint.

Municipality	P_m^+	P_m^u	Excluded	Urban (%)	Excl. (%)
Aradippou	22,932	22,474	458	98.0	2.0
Dromolaxia–Meneou	6,838	6,656	182	97.3	2.7
Kellia	387	345	42	89.3	10.7
Kiti	5,136	5,100	36	99.3	0.7
Larnaka	52,046	51,874	172	99.7	0.3
Livadia	8,581	8,459	122	98.6	1.4
Oroklini	7,575	7,509	66	99.1	0.9
Perivolia	3,920	3,907	13	99.7	0.3
Pyla	2,845	2,805	40	98.6	1.4
Total	**110,260**	**109,129**	**1,131**	**99.0**	**1.0**

Before any expansion algorithm is applied, the baseline graph and the existing-infrastructure interpretation determine an initial served population. Following Assumption A1, the southern municipalities, namely Larnaka, Dromolaxia–Meneou, Kiti, and Perivolia, are treated as the fully served WWTP1

brownfield context and therefore start at 100% urban coverage.

Table 7.2 shows that across the full modelled urban demand set, 70.3% is initially treated as served. This high value is driven by the southern brownfield context. Within the five northern expansion municipalities, coverage is much lower: approximately $32{,}462$ urban inhabitants require new network expansion, concentrated mainly in Aradippou, Livadia, and Oroklini.

Table 7.2: Initial urban coverage x_{m0} before network expansion. Southern municipalities are treated as the WWTP1 brownfield context and start at 100%.

Municipality	P_m^u	Served $S_0 \cap T_m$	x_{m0} (%)	Requiring exp.
Larnaka	51,874	51,874	100.0	0
Aradippou	22,474	4,102	18.3	18,372
Livadia	8,459	1,772	21.0	6,687
Oroklini	7,509	2,266	30.2	5,243
Kellia	345	0	0.0	345
Dromolaxia–Meneou	6,656	6,656	100.0	0
Perivolia	3,907	3,907	100.0	0
Kiti	5,100	5,100	100.0	0
Pyla	2,805	990	35.3	1,815
Total	**109,129**	**76,667**	**70.3**	**32,462**

The spatial distribution of the initial covered and uncovered urban demand is shown in Figure 7.1. Demand already associated with the existing wastewater-service context is concentrated primarily in the southern municipalities and in the partially served parts of the northern municipalities. Demand requiring expansion is distributed across all five northern municipalities, with the largest absolute concentrations in Aradippou, Livadia, and Oroklini.

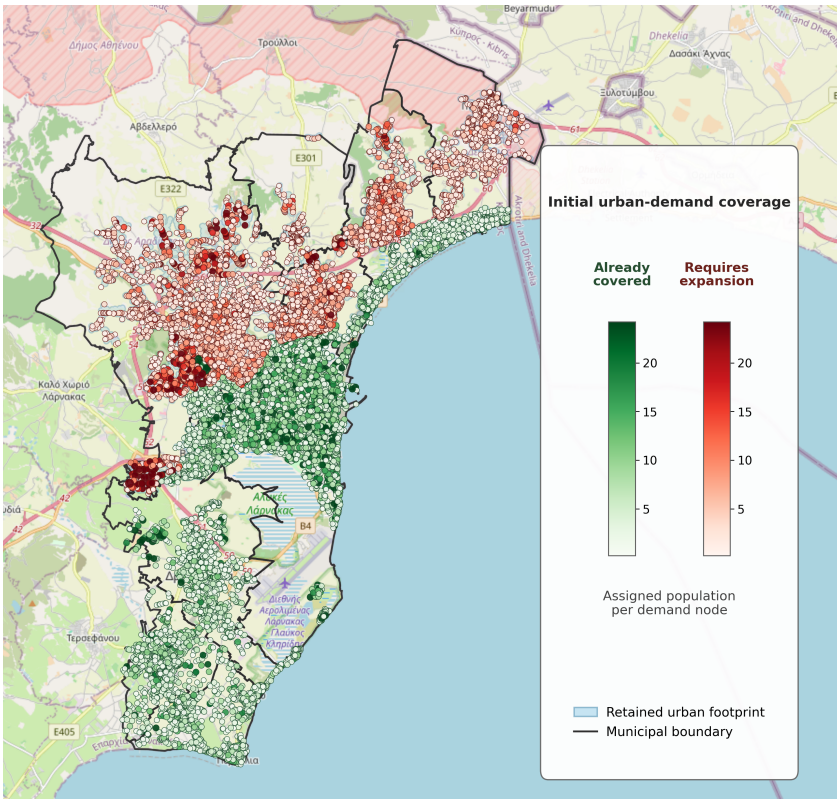


Figure 7.1: Initial urban-demand coverage across the Larnaka study area. Demand nodes derived from the retained urban footprint are classified as already covered or requiring expansion, while colour intensity indicates the population assigned to each demand node.

7.2. Phase 2 Results -- WWTP2 Endpoint Positioning

The rule-based screening of Phase 2 selects one root node r, which is used consistently by all five expansion configurations. The procedure considers $6{,}674$ demand nodes representing $30{,}329$ inhabitants in the admissible municipalities of Kellia, Oroklini, and Aradippou. Their population-weighted centroid is located at approximately $x = 555{,}271$ m and $y = 3{,}867{,}532$ m in EPSG:32636.

The geographic screening retains $3{,}909$ road-node candidates satisfying the municipal, northward-position, urban-clearance, and graph-component requirements. DEM screening then retains 392 candidates at or below the 10th-percentile elevation threshold of 60.34 m. The final minimum-score candidate is root node 30914, as summarised in Table 7.3.

Table 7.3: Selected WWTP2 planning-level endpoint and the principal quantities used to reproduce its selection. Distances and projected coordinates are rounded to the nearest metre, consistently with the planning-level spatial resolution of the analysis.

Quantity	Value
Root node r	30914
Longitude / latitude	33.6113, 34.9780
Projected coordinates (EPSG:32636)	$x = 555{,}795$ m; $y = 3{,}870{,}776$ m
Admissible municipalities	Kellia, Oroklini, Aradippou
Demand nodes considered	6,674
Population considered	30,329 inhabitants
Population-weighted centroid	$x = 555{,}271$ m; $y = 3{,}867{,}532$ m
Minimum admissible northing	$3{,}870{,}614$ m
Preferred northing	$3{,}871{,}214$ m
Geographically feasible candidates	3,909
Low-elevation threshold	60.34 m
Low-elevation candidates	392
Selected ground elevation	45.17 m
Distance to urban footprint	170.7 m
Distance to demand centroid	3,285.7 m
Northward clearance	161.7 m
Final site score s_j	3,431.0

The selected endpoint satisfies all eligibility conditions and has the lowest final site score within the retained low-elevation subset. It is a strategic treatment endpoint for configuration comparison and should not be interpreted as a permitted, hydraulically verified, or construction-ready wastewater treatment plant location. Figure 7.2 shows the selected endpoint in relation to the admissible municipalities and urban footprint.

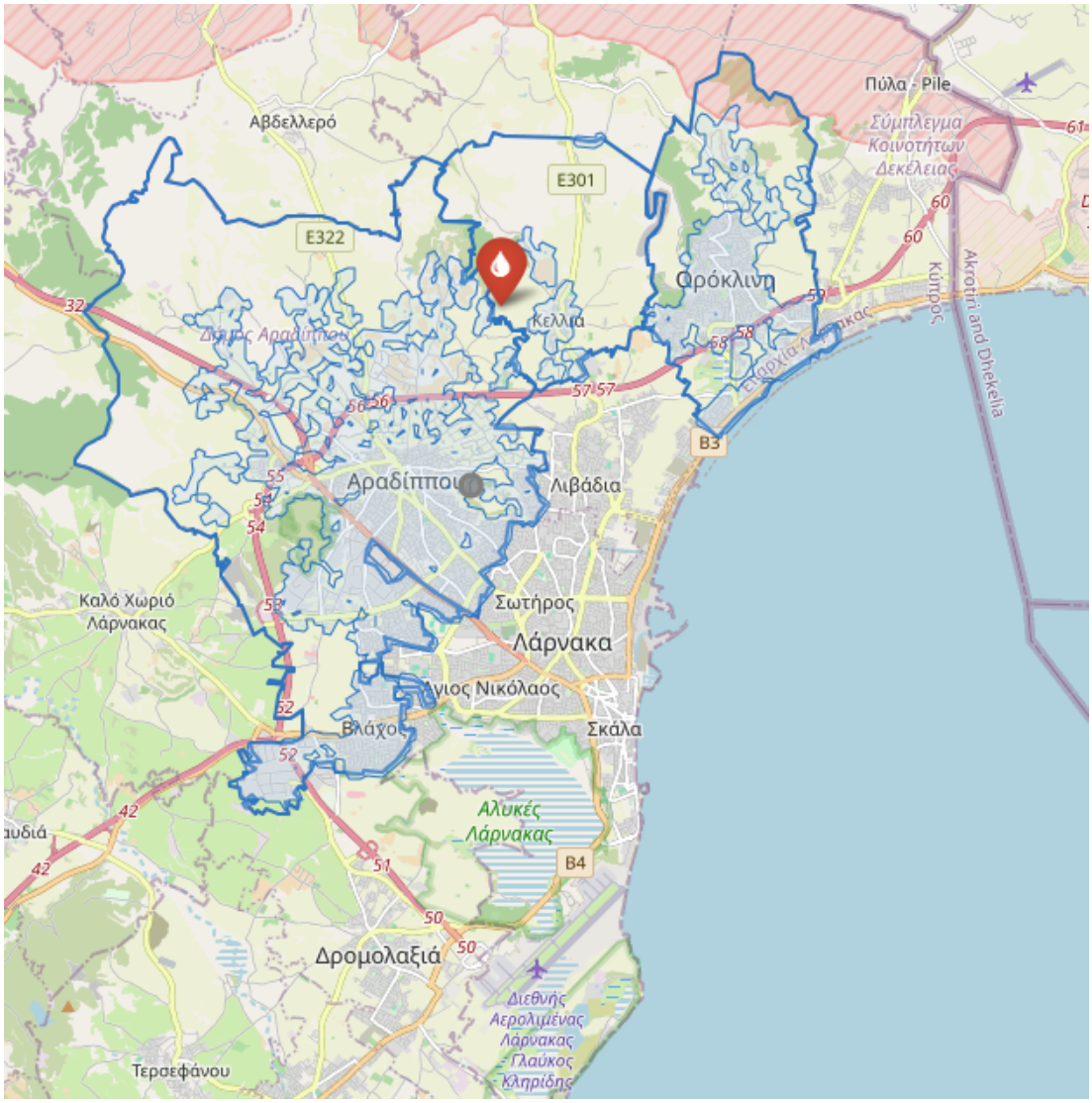


Figure 7.2: Selected planning-level WWTP2 root node r in relation to the urban footprint and the admissible municipalities of Kellia, Oroklini, and Aradippou. The endpoint is the minimum-score candidate remaining after application of the geographic, urban-clearance, graph-connectivity, snapping-distance, and low-elevation filters and is used as the common root of all five network configurations.

7.3. Phase 3 Results -- Network Expansion and Brownfield Allocation

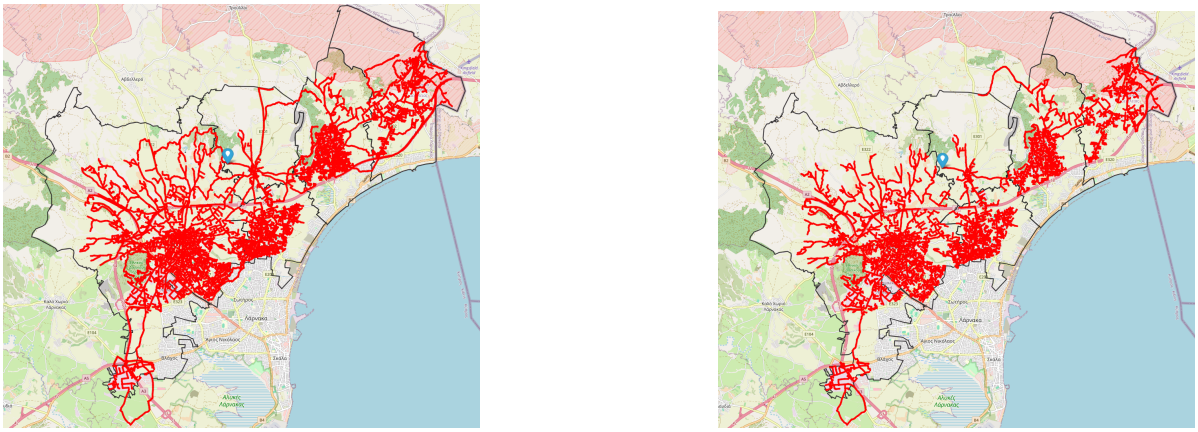
Phase 3 generates five network configurations connecting the urban terminals T to the WWTP2 root node r. Rooted Dijkstra and Prim–Steiner are non-budgeted full-urban-coverage references. Shared-trunk, Urban-priority, and Municipality-targets are budget-constrained configurations generated under the common pipe-length ceiling $\lambda_{\max} = \beta/c = 250$ km.

7.3.1. Generated Network Configurations

The two non-budgeted configurations both connect all modelled urban demand terminals and therefore reach full urban coverage by design. Rooted Dijkstra connects each terminal through its shortest path to r, whereas Prim–Steiner grows a connected tree and encourages greater corridor sharing. Figure 7.3 shows the resulting full-coverage layouts.

The three budget-constrained configurations all use approximately the same total pipe length but apply different prioritisation rules: Shared-trunk favours path-aware population gain, Urban-priority favours

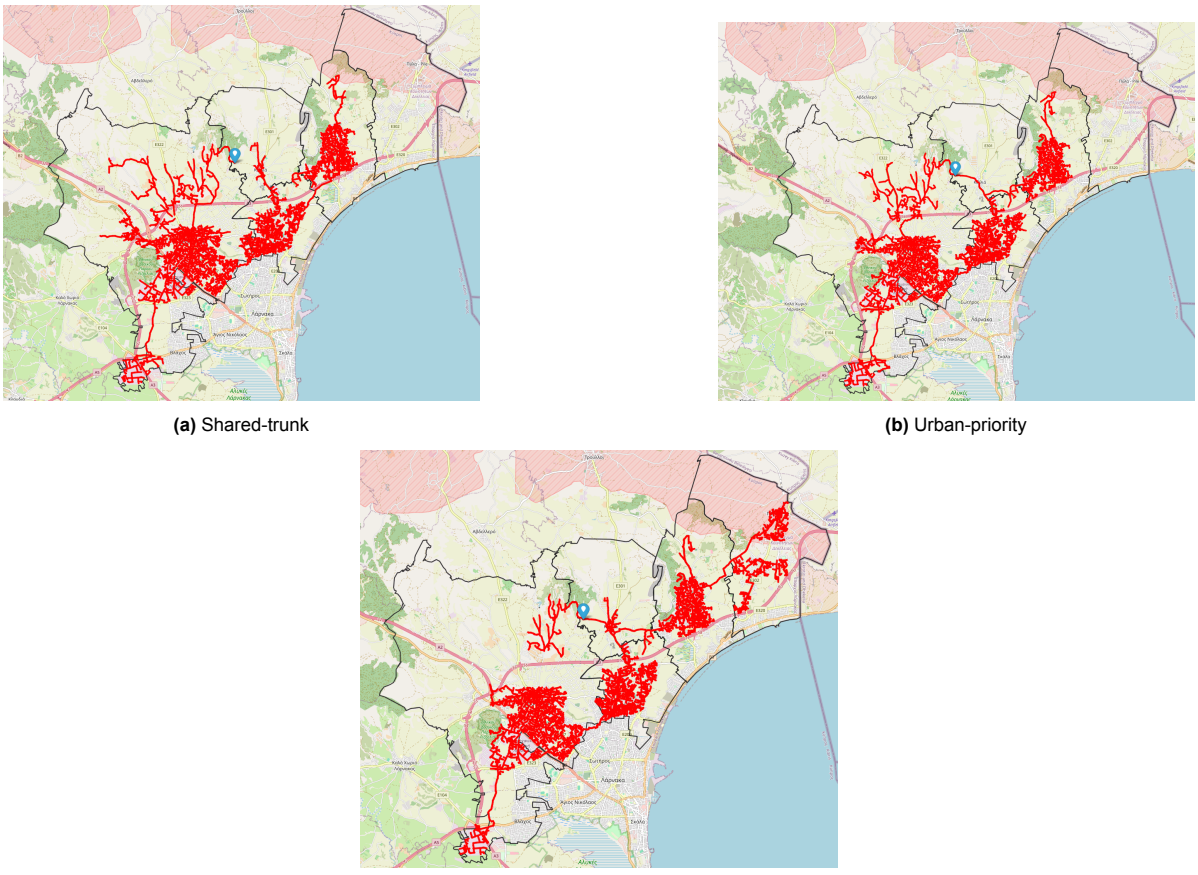
dense urban clusters, and Municipality-targets introduces staged municipal coverage objectives. Their resulting spatial layouts are shown in Figure 7.4.



(a) Rooted Dijkstra

(b) Prim–Steiner

Figure 7.3: Non-budgeted full-urban-coverage network configurations generated from the common WWTP2 root. Rooted Dijkstra forms the union of the single-source shortest paths to all urban terminals, whereas Prim–Steiner grows a shared tree by attaching each unconnected terminal to the network already constructed. Both reach 100% urban coverage.



(a) Shared-trunk

(b) Urban-priority

(c) Municipality-targets

Figure 7.4: Budget-constrained network configurations generated under the common new-pipe ceiling $\lambda_{\max} = 250$ km. Shared-trunk prioritises path-aware population gain, Urban-priority ranks candidate urban clusters by cluster-level gain, and Municipality-targets applies staged municipal coverage targets before allocating the residual budget.

7.3.2. Connectivity and Acyclicity Verification

All five generated network configurations passed the connectivity and acyclicity checks defined in Section 6.4. For each configuration, the selected new-pipe layout is connected to the WWTP2 root r, every served urban terminal has a path to the root, and the cyclomatic number is equal to zero. The selected layouts therefore contain no topological cycles, although line crossings or closely parallel corridors may appear visually in the maps. The complete verification results, including component counts, duplicate-corridor checks, root connectivity, and terminal-to-root connectivity, are reported in Appendix C.

7.3.3. Pipe Length and Pipe-Only Cost

Table 7.4 reports the selected new-pipe length $\ell(E')$ and the corresponding pipe-construction cost $C = c\,\ell(E')$. Rooted Dijkstra requires 494.6 km of new pipe, whereas Prim–Steiner requires 399.8 km, a difference of 94.8 km. Since both configurations achieve full urban coverage, their pipe-only costs differ by 38.0 M EUR. The three budget-constrained configurations each use approximately 250 km of new pipe and consequently have pipe-construction costs of approximately 100 M EUR.

Table 7.4: Selected new-pipe length and pipe-construction cost for the five network configurations, using the common unit cost $c = 400$ EUR m^{-1}.

Configuration	Family	$\ell(E')$ (km)	C (M EUR)
Rooted Dijkstra	Non-budgeted	494.6	197.9
Prim–Steiner	Non-budgeted	399.8	159.9
Shared-trunk	Budget-constrained	250.0	100.0
Urban-priority	Budget-constrained	250.0	100.0
Municipality-targets	Budget-constrained	249.9	100.0

7.3.4. Pre-Reconciliation Coverage and Raw WWTP Split

After the generation of the five network configurations, each configuration is first evaluated before the brownfield reassignment of existing conduits. At this stage, the WWTP2 load consists only of the urban population served by the newly generated WWTP2 network, while the southern brownfield context and the initially served existing-network demand remain assigned to WWTP1. This provides the raw pre-reconciliation WWTP split, before the existing-pipe reassignment procedure used to move the system toward the target WWTP2 share.

Table 7.5 reports the coverage indicators before brownfield reconciliation. The non-budgeted references achieve $x_u = 100\%$ by design. Among the budget-constrained configurations, Shared-trunk provides the highest urban coverage, with 97.5% and $106{,}360$ inhabitants served, followed by Urban-priority with 96.4% and Municipality-targets with 95.7%. As anticipated in Section 7.1, x_{tot} remains close to x_u because only 1.0% of the positive population lies outside the urban footprint.

Table 7.5: Pre-reconciliation coverage indicators. Urban coverage x_u is computed on T, while contextual total-population coverage x_{tot} is computed on D^+.

Configuration	Served	Uncovered	x_u (%)	x_{tot} (%)
Rooted Dijkstra	109,129	0	100.0	99.0
Prim–Steiner	109,129	0	100.0	99.0
Shared-trunk	106,360	2,769	97.5	96.5
Urban-priority	105,237	3,892	96.4	95.4
Municipality-targets	104,491	4,638	95.7	94.8

Table 7.6 reports the WWTP1/WWTP2 population split before application of the brownfield-allocation rule. The raw WWTP2 share ranges from 26.6% to 29.7%. These values represent the allocation produced by the generated WWTP2 configurations before the modelling target and manual spatial-coherence correction described in Section 6.4.5 are applied.

Table 7.6: Raw WWTP population split before the 40% brownfield reassignment step.

Configuration	Raw WWTP1 pop.	Raw WWTP2 pop.	Raw WWTP2 share (%)
Rooted Dijkstra	76,667	32,462	29.7
Prim–Steiner	76,667	32,462	29.7
Shared-trunk	76,667	29,693	27.9
Urban-priority	76,667	28,570	27.1
Municipality-targets	76,667	27,824	26.6

7.3.5. Existing-Pipe Assignment and Brownfield Reconciliation

The brownfield reconciliation procedure described in Section 6.4.5 is subsequently applied to interpret the existing conduits and pumping stations in relation to WWTP1 and WWTP2. The procedure first assigns conduits within the northern municipalities to WWTP2. It then extends the WWTP2 allocation near the transition between the two systems until the modelling target of approximately 40% is reached. Finally, the automatic result is manually reviewed to remove isolated fragments and spatially inconsistent assignments. The final step improves the spatial coherence of the planning-level allocation. Table 7.7 summarises the four reported states of the allocation, from the raw split to the manually corrected planning-level interpretation.

Table 7.7: Brownfield reconciliation stages used to assign existing assets to WWTP1 or WWTP2.

Stage	Operation	Purpose
0	Raw generated-network split	Initial WWTP1/WWTP2 interpretation before brownfield reassignment
1	Northern municipal assignment	Assign existing conduits inside northern municipality boundaries to WWTP2
2	Boundary-proximity reassignment	Add nearby existing conduits until the minimum WWTP2 share of 40% is reached
3	Manual correction	Remove isolated fragments and improve the spatial coherence of the final planning-level allocation

Table 7.8 reports the final WWTP1/WWTP2 population split after brownfield reconciliation. The adopted procedure increases the WWTP2 share from 26.6–29.7% in the raw generated-configuration allocation to 45.5–46.7% in the final planning-level interpretation. These shares result from the allocation rule adopted for this study and should not be interpreted as hydraulically derived or operationally required treatment-load shares.

Table 7.8: Post-reconciliation WWTP1/WWTP2 population split by configuration.

Configuration	WWTP1 pop.	WWTP2 pop.	Total served	WWTP1 (%)	WWTP2 (%)
Rooted Dijkstra	58,194	50,936	109,129	53.3	46.7
Prim–Steiner	58,798	50,331	109,129	53.9	46.1
Shared-trunk	57,964	48,397	106,360	54.5	45.5
Urban-priority	56,484	48,753	105,237	53.7	46.3
Municipality-targets	56,542	47,949	104,491	54.1	45.9

Tables 7.9 and 7.10 report the municipal-level post-reconciliation interpretation. The northern municipalities are almost entirely assigned to WWTP2 after reconciliation, while the southern brownfield municipalities remain predominantly assigned to WWTP1. Some southern demand, especially in Larnaka and a small share of Dromolaxia–Meneou, is reassigned to WWTP2 as a result of the boundary-proximity and manual reconciliation steps. This is the mechanism that produces the final two-system allocation reported in Table 7.8.

Table 7.9: Municipal-level WWTP1/WWTP2 population split and municipal urban coverage x_m after brownfield reconciliation for the northern expansion municipalities.

Municipality	Configuration	WWTP1 pop.	WWTP2 pop.	Total served	WWTP2 (%)	x_m (%)
Aradippou	Dijkstra	12	22,463	22,474	99.9	100.0
Aradippou	Prim–Steiner	18	22,456	22,474	99.9	100.0
Aradippou	Shared-trunk	0	21,743	21,743	100.0	96.7
Aradippou	Urban-priority	0	20,791	20,791	100.0	92.5
Aradippou	Muni-targets	0	18,642	18,642	100.0	82.9
Livadia	Dijkstra	0	8,459	8,459	100.0	100.0
Livadia	Prim–Steiner	0	8,459	8,459	100.0	100.0
Livadia	Shared-trunk	0	8,413	8,413	100.0	99.5
Livadia	Urban-priority	0	8,429	8,429	100.0	99.6
Livadia	Muni-targets	0	8,400	8,400	100.0	99.3
Oroklini	Dijkstra	0	7,509	7,509	100.0	100.0
Oroklini	Prim–Steiner	0	7,509	7,509	100.0	100.0
Oroklini	Shared-trunk	0	7,375	7,375	100.0	98.2
Oroklini	Urban-priority	0	7,380	7,380	100.0	98.3
Oroklini	Muni-targets	0	7,185	7,185	100.0	95.7
Kellia	Dijkstra	0	345	345	100.0	100.0
Kellia	Prim–Steiner	0	345	345	100.0	100.0
Kellia	Shared-trunk	0	303	303	100.0	87.8
Kellia	Urban-priority	0	110	110	100.0	31.9
Kellia	Muni-targets	0	262	262	100.0	75.9
Pyla	Dijkstra	0	2,805	2,805	100.0	100.0
Pyla	Prim–Steiner	0	2,805	2,805	100.0	100.0
Pyla	Shared-trunk	0	990	990	100.0	35.3
Pyla	Urban-priority	0	990	990	100.0	35.3
Pyla	Muni-targets	0	2,466	2,466	100.0	87.9

Table 7.10: Municipal-level WWTP1/WWTP2 population split and municipal urban coverage x_m after brownfield reconciliation for the southern brownfield municipalities.

Municipality	Configuration	WWTP1 pop.	WWTP2 pop.	Total served	WWTP2 (%)	x_m (%)
Larnaka	Dijkstra	42,826	9,048	51,874	17.4	100.0
Larnaka	Prim–Steiner	43,424	8,450	51,874	16.3	100.0
Larnaka	Shared-trunk	42,485	9,389	51,874	18.1	100.0
Larnaka	Urban-priority	41,009	10,866	51,874	20.9	100.0
Larnaka	Muni-targets	40,999	10,875	51,874	21.0	100.0
Dromolaxia–Meneou	Dijkstra	6,350	306	6,656	4.6	100.0
Dromolaxia–Meneou	Prim–Steiner	6,350	306	6,656	4.6	100.0
Dromolaxia–Meneou	Shared-trunk	6,472	184	6,656	2.8	100.0
Dromolaxia–Meneou	Urban-priority	6,469	187	6,656	2.8	100.0
Dromolaxia–Meneou	Muni-targets	6,537	119	6,656	1.8	100.0
Perivolia	Dijkstra	3,907	0	3,907	0.0	100.0
Perivolia	Prim–Steiner	3,907	0	3,907	0.0	100.0
Perivolia	Shared-trunk	3,907	0	3,907	0.0	100.0
Perivolia	Urban-priority	3,907	0	3,907	0.0	100.0
Perivolia	Muni-targets	3,907	0	3,907	0.0	100.0
Kiti	Dijkstra	5,100	0	5,100	0.0	100.0
Kiti	Prim–Steiner	5,100	0	5,100	0.0	100.0
Kiti	Shared-trunk	5,100	0	5,100	0.0	100.0
Kiti	Urban-priority	5,100	0	5,100	0.0	100.0
Kiti	Muni-targets	5,100	0	5,100	0.0	100.0

Of the 22 existing pumping stations, 13 are allocated to the WWTP2 service area and 9 remain associated with WWTP1 after the final brownfield reconciliation. This allocation is stable across all five configurations. As shown in Figure 7.5, the stations assigned to WWTP2 are concentrated around the northern and coastal parts of the study area and are located nearest to the final WWTP2 pipe system. The remaining stations are retained within the southern WWTP1 service area. The station codes displayed in the figure correspond to the existing pumping-station identifiers used throughout the analysis. The Phase 4 configuration maps subsequently show these existing stations together with the new pumping-station candidates identified by the feasibility screening.

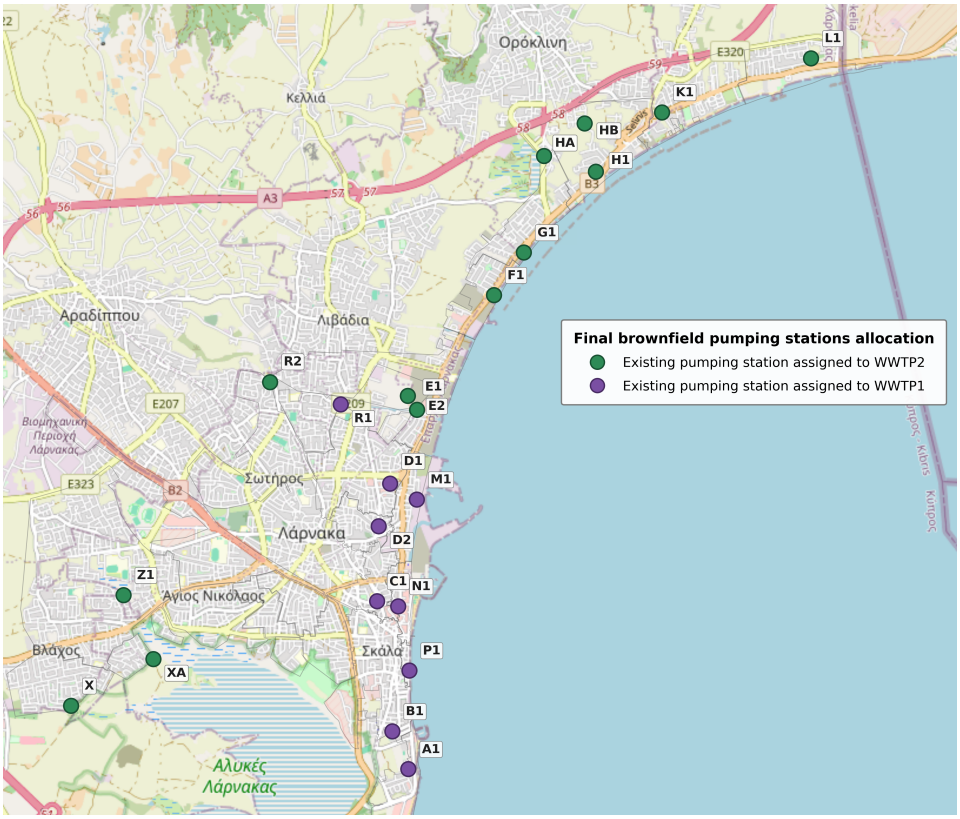


Figure 7.5: Final planning-level allocation of the 22 stakeholder-provided existing pumping stations after brownfield reconciliation. Thirteen stations are associated with the WWTP2 service area and nine remain associated with WWTP1.

7.4. Phase 4 Results -- Pumping-Feasibility Screening

Phase 4 screens each corrected network for sections where the required excavation depth would exceed the maximum admissible gravity cover $\delta_{\max}$. The threshold is calibrated from the 90th percentile of the recorded `MaxDepth` values in the existing pumping-station layer. Since the computed value is 8.63 m and the default floor is 8.0 m, the screening uses $\delta_{\max} = 8.63$ m for all configurations.

7.4.1. Retained Pumping-Station Candidates

Table 7.11 reports the retained candidate set K', separated into mandatory and optional stations. Rooted Dijkstra retains 30 candidates, Prim–Steiner 26, Shared-trunk 20, Urban-priority 18, and Municipality-targets 20. Mandatory stations account for 29 of 30 retained candidates for Rooted Dijkstra, all 26 for Prim–Steiner, 19 of 20 for Shared-trunk, and all retained candidates for Urban-priority and Municipality-targets.

Table 7.11: Retained pumping-station candidates $|K'|$ by configuration, using $\delta_{\max} = 8.63$ m.

Configuration	Family	$\ell(E')$ (km)	$\lvert K' \rvert$	Mandatory	Optional
Rooted Dijkstra	Non-budgeted	494.6	30	29	1
Prim–Steiner	Non-budgeted	399.8	26	26	0
Shared-trunk	Budget-constrained	250.0	20	19	1
Urban-priority	Budget-constrained	250.0	18	18	0
Municipality-targets	Budget-constrained	249.9	20	20	0

7.4.2. Pumping CAPEX and Adjusted Configuration Cost

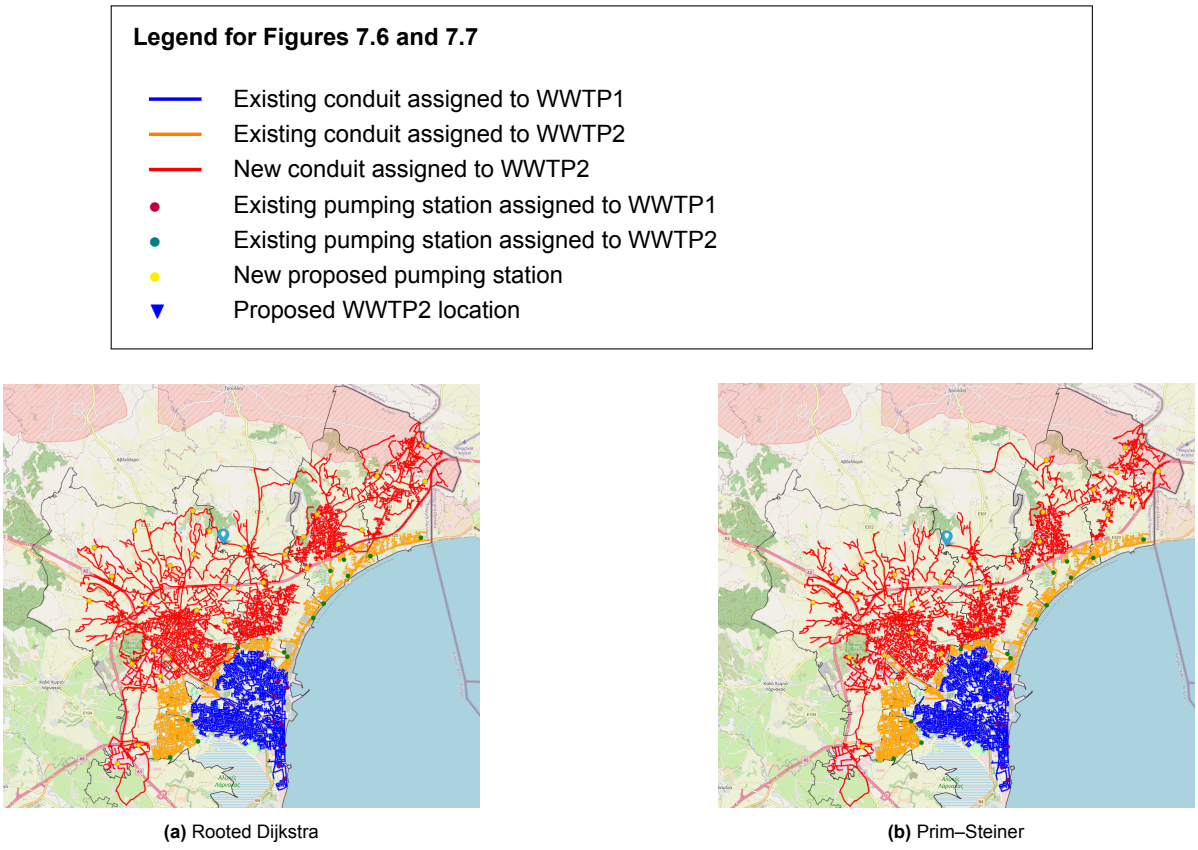
Adding pumping CAPEX, $h\,|K'|$, to the pipe cost gives the total configuration cost $z = C + h\,|K'|$, shown in Table 7.12. The key planning result is that the pipe-only 100 M EUR budget of the budget-

constrained configurations is not the full cost picture. Once pumping is included, the budget-constrained configurations reach about 127.0–130.0 M EUR, moving them into the upper part of the 100–150 M EUR envelope. The non-budgeted references reach 198.9 M EUR for Prim–Steiner and 242.9 M EUR for Rooted Dijkstra, well beyond the budgeted range.

Table 7.12: Pumping CAPEX and total configuration cost $z = C + h\,|K'|$, using $h = 1.5$ M EUR per station.

Configuration	$h\,\lvert K'\rvert$ (M EUR)	z (M EUR)	Existing PS $\rightarrow$ WWTP2
Rooted Dijkstra	45.0	242.9	13
Prim–Steiner	39.0	198.9	13
Shared-trunk	30.0	130.0	13
Urban-priority	27.0	127.0	13
Municipality-targets	30.0	130.0	13

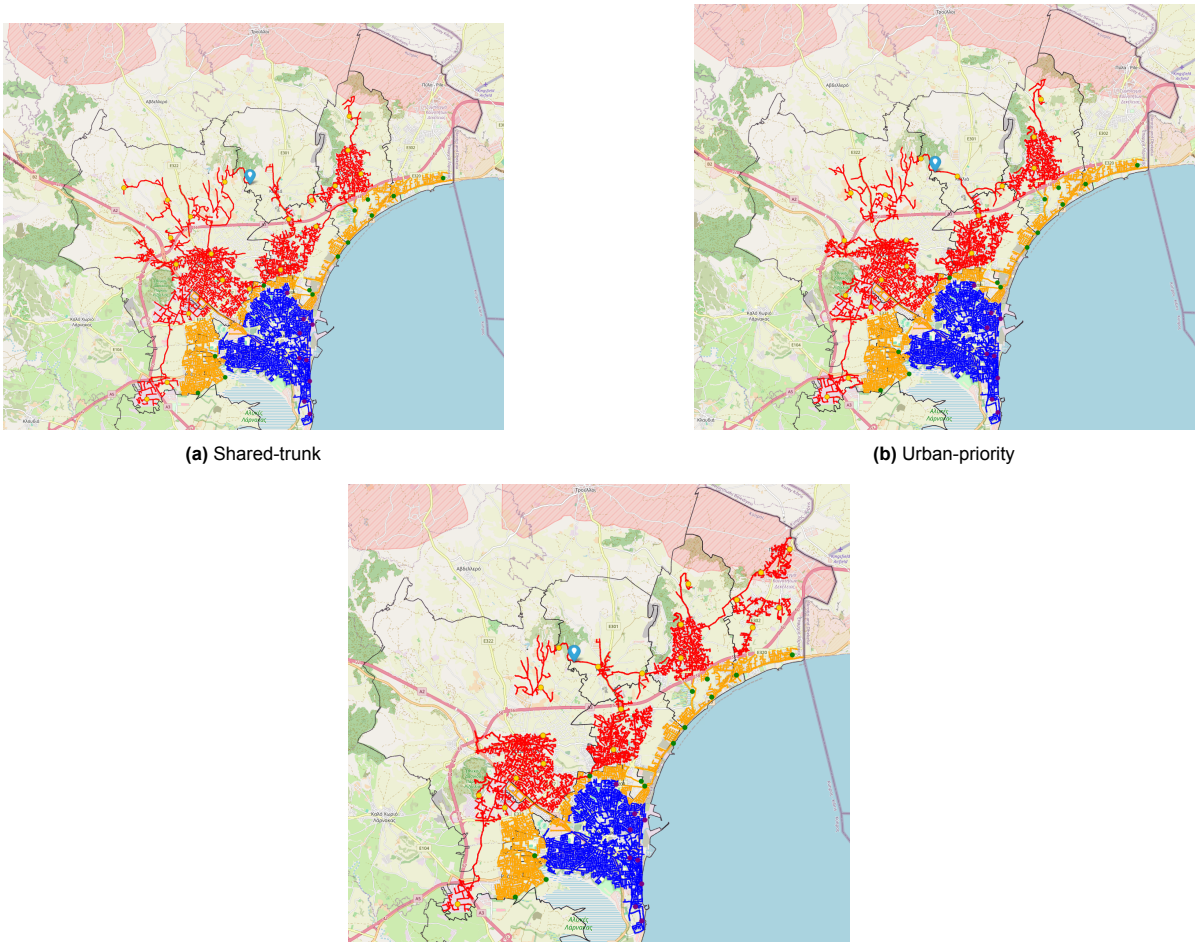
The final spatial outputs are shown in Figures 7.6 and 7.7. These maps combine the corrected allocation of existing conduits between WWTP1 and WWTP2 from Phase 3 with the pumping-feasibility screening of Phase 4. They therefore represent the final planning-level network configurations after brownfield reconciliation and pumping-station positioning. Existing conduits assigned to WWTP1 and WWTP2 are shown separately, newly constructed conduits are highlighted, and both existing and newly proposed pumping stations are included.



(a) Rooted Dijkstra

(b) Prim–Steiner

Figure 7.6: Final non-budgeted network configurations after brownfield reconciliation and pumping-feasibility screening. The maps distinguish existing conduits assigned to WWTP1 and WWTP2, new WWTP2 conduits, existing pumping stations associated with each treatment system, retained new pumping-station candidates, and the common WWTP2 endpoint.



(a) Shared-trunk

(b) Urban-priority

(c) Municipality-targets

Figure 7.7: Final budget-constrained network configurations after brownfield reconciliation and pumping-feasibility screening. All three configurations use approximately the same new-pipe length, while the maps show the resulting differences in corridor allocation, municipal service distribution, and retained pumping-station locations.

7.5. Phase 5 Results -- Configuration Evaluation and Comparative Assessment

The final phase compares the five configurations using the indicators defined in Section 6.6. Table 7.13 consolidates new-pipe length, urban and total-population coverage, municipal distribution, pumping requirements, total capital cost, cost per inhabitant served, and the final WWTP2 population share.

Municipal distribution is reported through the standard deviation σ_x and the minimum municipal coverage $x^{\min}$ across the five northern municipalities. The two non-budgeted configurations reach $x_m = 100\%$ in every northern municipality. Among the budget-constrained configurations, Shared-trunk has $\sigma_x = 24.4$ percentage points and $x^{\min} = 35.3\%$; Urban-priority has $\sigma_x = 31.1$ percentage points and $x^{\min} = 31.9\%$; and Municipality-targets has $\sigma_x = 8.5$ percentage points and $x^{\min} = 75.9\%$.

7.5.1. Integrated Configuration Comparison

Both non-budgeted configurations reach 100% urban coverage. Compared with Rooted Dijkstra, Prim–Steiner uses 94.8 km less new pipe, retains four fewer pumping-station candidates, and has a total capital cost that is 44.0 M EUR lower.

The three budget-constrained configurations use approximately the same new-pipe length and have total capital costs between 127.0 and 130.0 M EUR. Their urban coverage ranges from 95.7% to 97.5%, while their minimum municipal coverage ranges from 31.9% to 75.9%. Shared-trunk serves the largest

aggregate urban population. Urban-priority has the lowest total cost, while Municipality-targets has the lowest municipal coverage dispersion among the budget-constrained configurations.

Table 7.13: Integrated comparison of the five network configurations. Urban coverage x_u is computed over T, total-population coverage x_{tot} over D^+, municipal dispersion σ_x across the five northern municipalities, and total cost per inhabitant $u = z/\sum_{i\in S} p_i$. Total cost includes new-pipe construction and retained new pumping-station candidates.

Configuration	Family	$\ell(E')$ (km)	x_u (%)	x_{tot} (%)	σ_x (pp)	$x^{\min}$ (%)	$\lvert K'\rvert$	z (M EUR)	u (EUR/cap)	WWTP2 (%)
Rooted Dijkstra	Non-budgeted	494.6	100.0	99.0	0.0	100.0	30	242.9	2,225	46.7
Prim–Steiner	Non-budgeted	399.8	100.0	99.0	0.0	100.0	26	198.9	1,823	46.1
Shared-trunk	Budget-constrained	250.0	97.5	96.5	24.4	35.3	20	130.0	1,222	45.5
Urban-priority	Budget-constrained	250.0	96.4	95.4	31.1	31.9	18	127.0	1,207	46.3
Municipality-targets	Budget-constrained	249.9	95.7	94.8	8.5	75.9	20	130.0	1,244	45.9

Figure 7.8 plots the total capital cost against urban population coverage. The two full-coverage references are separated from the three budget-constrained configurations primarily by total cost, whereas the budget-constrained points occupy a narrow range of both cost and aggregate coverage.

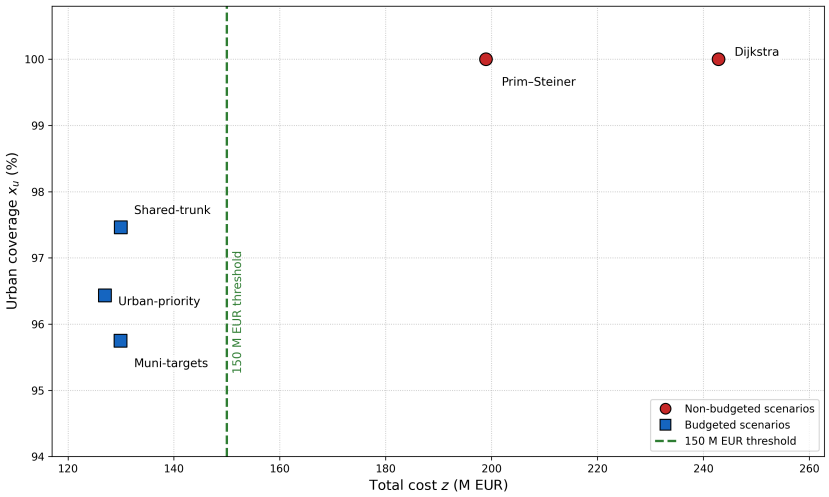


Figure 7.8: Total capital cost and urban population coverage for the five network configurations. Costs include new-pipe construction and retained new pumping-station candidates. The three budget-constrained configurations cluster between 95.7% and 97.5% urban coverage and between 127.0 and 130.0 M EUR, while the two non-budgeted full-coverage references have higher total capital costs.

The spatial and quantitative results reported in this chapter provide the basis for the subsequent discussion. Chapter 8 interprets the differences between the five configurations in relation to financial realism, municipal distribution, regulatory relevance, brownfield integration, and the limitations of the planning-level model.

8

Discussion

This chapter interprets the results presented in Chapter 7 and reflects on what they imply for wastewater planning in the northern Larnaka District. It is organised around four themes: the comparison and interpretation of the two configuration families, the broader implications and transferability of the approach, the limitations of the modelling choices, and the practical recommendations for the Local District Government Organisation of Larnaka.

8.1. Configuration Comparison and Interpretation

8.1.1. Non-Budgeted Configurations: The Cost of Full Urban Coverage

The two non-budget-constrained configurations were not developed as directly buildable proposals, but as full-coverage reference configurations for the Local District Government Organisation of Larnaka. Their purpose is to quantify the approximate infrastructure scale associated with connecting all modelled urban demand in the northern service area to WWTP2, before introducing the budget constraint. In this sense, they answer an informative planning question: what would full urban coverage cost if the district decided to pursue complete immediate connection of the modelled northern demand?

Both Rooted Dijkstra and Prim–Steiner reach 100% urban coverage, but they do so through different routing logics and therefore at substantially different cost. Rooted Dijkstra produces 494.6 km of new pipe at an estimated total cost of 242.9 M EUR, while Prim–Steiner requires 399.8 km and 198.9 M EUR. The difference, 94.8 km and 44.0 M EUR, is not caused by different demand assumptions, since both configurations serve the same terminal set. It is caused by the structure of the network generated by the two heuristics.

Rooted Dijkstra optimises the connection of each urban terminal individually: every terminal is routed to the WWTP2 root through its shortest available path, and the final network is the union of these individual paths. This makes the result transparent and easy to interpret, because each connection can be traced back to a shortest route from one demand point to the treatment endpoint. However, this logic does not explicitly minimise the total length of the combined network. Shared corridors appear only where individual shortest paths happen to overlap. As a result, the Dijkstra union can contain redundant parallel branches and a less compact trunk structure.

Prim–Steiner adopts a more network-oriented logic. Instead of treating each terminal as an independent routing problem, it progressively grows a connected tree from the root and attaches new terminals to the nearest existing branch. This does not necessarily give every terminal its own shortest route to WWTP2, but it reduces the cumulative length of the combined network by encouraging corridor sharing. The result is therefore a more compact trunk skeleton, with less duplicated infrastructure and lower total cost. The comparison shows that, in sewer expansion planning, individually shortest connections are not equivalent to a collectively efficient network.

This result connects directly to the argument developed in the literature review. Classical shortest-path algorithms [20], [21] are useful foundations for graph-based sewer planning, but they are insufficient

when the planning problem involves multiple demand areas, shared corridors, existing assets, and aggregate construction cost. A wastewater collection network is not a set of independent point-to-point links; it is a spatial infrastructure system whose cost depends strongly on how connections are combined. The improvement from Rooted Dijkstra to Prim–Steiner therefore illustrates why sewer network expansion requires methods that draw on tree-based and constrained network-design formulations [22], [23] rather than a simple shortest-path baseline.

From a practical perspective, Rooted Dijkstra should be interpreted as a transparent shortest-path reference for the cost of full coverage, rather than as a realistic candidate plan. Prim–Steiner is the more relevant full-coverage reference because it achieves the same coverage with a shorter network, lower total cost, and slightly fewer pumping-station candidates (26 versus 30). Nevertheless, even Prim–Steiner remains above the 100 to 150 M EUR budget envelope: its adjusted cost exceeds the upper end of the envelope by 48.9 M EUR. The non-budget-constrained configurations therefore confirm that complete immediate coverage of all modelled urban demand is unlikely to be financially realistic within the indicated budget. Their value is instead to quantify the scale of the shortfall and to establish a benchmark against which the budget-constrained configurations can be interpreted.

8.1.2. Budget-Constrained Configurations: Coverage Under Limited Funding

The budget-constrained configurations represent the most policy-relevant part of the configuration comparison, because they move from the theoretical cost of full coverage to the practical question of how a limited investment budget could be spatially allocated. Shared-trunk, Urban-priority, and Municipality-targets all saturate the available pipe-length budget of approximately 250 km, corresponding to 100 M EUR in pipe construction cost at the adopted unit rate of 400 EUR/m. Since the pipe-cost model is linear in length, the pipe-only cost of the three configurations is almost identical by construction. Their differences are therefore not primarily economic, but spatial and distributional: each heuristic uses the same infrastructure budget according to a different planning logic.

Shared-trunk provides the highest aggregate urban coverage, reaching 97.5% of the modelled urban population, equivalent to 106,360 served inhabitants. This configuration does not impose an explicit municipal or urban-density priority. Instead, it rewards path-aware population gain, meaning that a connection becomes attractive when it serves demand not only at the target node but also along the route used to reach it. The resulting network can therefore be interpreted as an efficiency-oriented shared-corridor solution: it uses the fixed pipe budget to maximise the number of inhabitants connected through trunk-like extensions. However, because the heuristic is driven by aggregate gain, it does not guarantee that coverage is evenly distributed across municipalities. Areas that are close to, or aligned with, the main trunk corridors are favoured, while smaller or more peripheral settlements may remain comparatively weakly served.

Urban-priority applies a different logic. Rather than rewarding all demand encountered along a connecting route, it prioritises dense urban clusters. This makes the configuration more directly aligned with the objective of serving the main concentrations of wastewater demand. It reaches 96.4% urban coverage, slightly below Shared-trunk, but its spatial interpretation is different: the network is less a generic shared-corridor expansion and more an urban-concentration strategy. In planning terms, this configuration answers the question of what happens when the fixed budget is directed first toward the most populated urban areas, accepting that less dense or spatially peripheral demand may be postponed.

Municipality-targets introduces a third logic. Its overall coverage, 95.7%, is close to Urban-priority, but the rationale is substantially different. Instead of maximising only aggregate coverage or prioritising the densest urban clusters, it imposes staged municipal coverage objectives. This makes the configuration more municipality-balanced: part of the available infrastructure budget is effectively reserved to improve coverage in smaller municipalities such as Kellia and Pyla, even when those connections are less efficient in terms of inhabitants served per kilometre of pipe. This is most visible at municipal level: as reported in Table 7.9, Pyla rises from 35.3% coverage under Shared-trunk and Urban-priority to 87.9% under Municipality-targets, and Kellia from 31.9% under Urban-priority to 75.9%, while Aradippou is reduced from 96.7% to 82.9%. The small reduction in total coverage is therefore the cost of a more deliberate redistribution of service from the larger towards the smaller northern municipalities.

The comparison between the three budget-constrained configurations shows that the main planning

trade-off is not between configurations with different pipe-budget compliance, because all three remain within the same pipe-length budget. The trade-off is between three different interpretations of what the budget should achieve. Shared-trunk maximises aggregate coverage through shared-corridor efficiency. Urban-priority concentrates investment on the main urban demand clusters. Municipality-targets sacrifices a small amount of total coverage to obtain a more balanced municipal distribution. The coverage gap between the highest- and lowest-performing budget-constrained configurations is 1.8 percentage points, corresponding to 1,869 inhabitants (the difference between the 106,360 served by Shared-trunk and the 104,491 served by Municipality-targets), but the spatial meaning of that gap is important: it determines whether the remaining unserved population is concentrated in smaller municipalities or distributed according to a more explicit service-equity logic.

This distinction has direct regulatory and planning relevance. Directive (EU) 2024/3019 lowers the mandatory collection-and-treatment threshold from 2000 PE to 1000 PE, bringing smaller agglomerations within the scope of collective wastewater obligations. A purely efficiency-oriented strategy may maximise the number of inhabitants served, but still leave specific smaller settlements insufficiently connected. Conversely, a municipality-balanced strategy may appear slightly less efficient in aggregate terms while being more consistent with a phased compliance strategy for the whole northern service area, reflecting the distributional and long-term prioritisation criteria emphasised in sustainable urban water management [6], [24].

The municipal-level results of Table 7.9 make this regulatory argument concrete. Using the modelled municipal urban population as a planning-level proxy for agglomeration size, four of the five northern municipalities fall within the scope of the Directive, while Kellia, at 345 PE, does not. Among the in-scope municipalities, Aradippou, Livadia, and Oroklini remain substantially served under all three budgeted configurations, with residual gaps confined to their peripheral fringe. The critical case is Pyla: an in-scope agglomeration of 2,805 PE that the two efficiency-oriented configurations leave roughly two-thirds unconnected ($x_m = 35.3\%$). Because the Directive attaches obligations to individual agglomerations rather than to district-wide totals, this is precisely the configuration in which high aggregate coverage can coexist with non-compliance for a specific settlement. Municipality-targets does not fully close the Pyla gap either, but it changes its nature: from an agglomeration left substantially unserved to a residual of 339 inhabitants that a later phase can complete or that duly justified individual systems can cover. The improved coverage of Kellia under the same configuration is, by contrast, a service-equity outcome rather than a compliance requirement. Two caveats apply: the modelled urban population is only a proxy, and a formal delineation of agglomerations under the Directive lies beyond the scope of this model and is left to the subsequent design stage.

The choice between the three budget-constrained heuristics is therefore not simply a technical optimisation choice; it is a planning decision about whether Larnaka should prioritise maximum aggregate coverage, urban concentration, or a more balanced municipal expansion path, and the Pyla case shows that this decision carries direct compliance implications.

8.1.3. Cross-Family Comparison: What the Two Families Tell the Planner

Comparing the two configuration families reveals two results with direct planning value.

The first is the marginal cost of the final percentage points of coverage. The budget-constrained configurations achieve 95.7 to 97.5% urban coverage for 127.0 to 130.0 M EUR, including pumping CAPEX. Reaching 100% urban coverage through the more compact Prim–Steiner reference raises total cost to 198.9 M EUR, an increase of 68.9 M EUR relative to Shared-trunk despite adding only the final 2.5 percentage points of urban coverage. The comparison is not a literal phasing sequence, because the configurations are generated independently, but it shows that the remaining peripheral demand is associated with a disproportionately large increase in network length and capital cost. The finding is consistent with the connection-cost literature, which shows that the unit cost of sewering rises as settlements become more sparse and distant [4]. In the Larnaka case, this means that a deliberate decision about where to stop extending the network is a core planning outcome, not a residual technical detail.

The second result concerns the effect of pumping on the interpretation of the budget. The budget-constrained configurations respect the pipe-only ceiling of 100 M EUR, but once the pumping-feasibility screening adds the capital cost of 18 to 20 new stations at 1.5 M EUR each, they rise to 127.0 to

130.0 M EUR, entering the upper part of the 100 to 150 M EUR financial envelope. The non-budgeted references rise even further. In the flat coastal terrain of the Larnaka District, evaluating candidate network layouts only by pipe length and pipe cost is therefore misleading: gravity conveyance is fragile, pumping requirements are not marginal, and the pumping-feasibility screening materially changes which configurations remain comfortably within the financial envelope. The screening is not a cosmetic complement but an integral part of the cost assessment.

Together, the two configuration families allow the planner to read the planning problem from two directions. The non-budgeted references answer the question “what would full coverage cost?” and show that it exceeds the indicated budget. The budget-constrained configurations answer the question “how much coverage can the budget buy, and how should it be distributed?” and show that near-complete coverage is achievable but that its spatial distribution depends on the planning logic adopted. Neither family replaces the other: the non-budget-constrained configurations set the scale, and the budget-constrained configurations explore the trade-offs within the financially realistic range.

8.2. Broader Implications and Transferability

8.2.1. Position in the Planning Pipeline

The approach developed in this thesis occupies an intermediate layer between master-planning and detailed engineering design. Master-planning defines the broad configuration of the wastewater system, for example whether a region should be served by one centralised system, by several decentralised systems, or by a hybrid arrangement. Detailed engineering design then translates a selected option into pipe diameters, invert levels, pumping-station specifications, pressure-main design, and construction-ready drawings. The model developed here sits between these two levels. Its purpose is not to produce a final sewer design, but to provide a strategic screening tool that helps planners understand what different expansion logics can achieve before detailed hydraulic design is started.

This intermediate position is important for the Larnaka case because the planning problem is not defined only by one technical objective. The Local District Government Organisation needs to understand the approximate cost of full urban coverage, the level of coverage that can be achieved within the available budget, and the spatial consequences of adopting different planning priorities. The non-budget-constrained configurations show the infrastructure scale associated with complete immediate coverage. The budget-constrained configurations show what can be achieved under a realistic pipe-length budget. The different heuristics then show how the same investment envelope can lead to different outcomes depending on whether the priority is shared-corridor efficiency, dense urban coverage, or a more balanced municipal distribution.

The main value of the model is therefore not the identification of a single optimal network. Rather, it structures the planning conversation around explicit trade-offs: full coverage versus financial realism, aggregate efficiency versus municipal balance, urban concentration versus peripheral inclusion, and pipe-only cost versus pumping-inclusive cost. This type of output is particularly useful at an early planning stage, when the decision-maker needs to compare possible directions for investment before committing resources to detailed engineering studies.

8.2.2. Applicability to Other Partially Served Districts

The modelling framework is transferable because it is based on a generic sequence of planning steps: constructing a corridor-based graph, representing wastewater demand, defining a treatment endpoint, generating alternative expansion configurations, screening for pumping requirements, and comparing the resulting layouts through coverage, cost, and distributional indicators. This sequence is not specific to Larnaka. In principle, it could be replicated in other partially served districts where wastewater demand is spatially distributed and where planners need to compare network expansion options under financial or technical constraints.

The data requirements are also relatively accessible. The road corridor graph can be derived from OpenStreetMap [16]; building footprints can be used as a demand proxy; terrain can be obtained from a digital elevation model; population can be taken from municipal or census statistics; and existing sewer assets can be incorporated when local utilities provide them. This makes the approach suitable for contexts where detailed hydraulic information is not yet available, but where a first spatially explicit

estimate of network length, cost, coverage, and pumping exposure is needed.

However, transferability does not mean that the Larnaka calibration can be copied directly. Several elements would need to be adapted to the local context. These include the treatment endpoint selection rules, the definition of urban demand terminals, the cost assumptions, the pumping-screening thresholds, the treatment of existing assets, and any municipality-specific coverage targets. The framework is therefore flexible, but not universal in its parameterisation. It provides a reusable planning structure, while the local data and local policy priorities determine how that structure should be calibrated.

8.2.3. Scope of the Model

The scope of the model is strategic decision support. It gives Larnaka an approximate but spatially explicit understanding of what different wastewater expansion strategies could achieve under different assumptions. With no budget constraint, the model estimates the scale and cost of full urban coverage. With a fixed budget, it estimates how much of the northern urban demand can be served and how that coverage is distributed. With different heuristics, it shows how the same budget can support different planning priorities, such as maximum aggregate coverage, urban-cluster prioritisation, or municipal balance.

This scope is deliberately broader than a simple cost estimate but narrower than a full engineering design. The model connects demand, corridors, costs, coverage, existing assets, and pumping indicators in a single spatial framework, but it does not verify hydraulic capacity. It imposes no pipe-diameter constraints, no treatment-plant capacity constraints, and no detailed invert-level design. A demand node is counted as served when it is topologically connected to the selected network, regardless of whether the downstream hydraulic capacity has been proven. Similarly, the pumping-feasibility screening identifies locations where pumping is likely, but it does not size pumps, pressure mains, or wet wells.

The configuration outputs should therefore be read as planning hypotheses rather than buildable network designs. Their role is to help Larnaka decide which type of expansion strategy is worth developing further. Once a preferred direction is selected, the corresponding layout would need to be tested through hydraulic modelling, refined cost estimation, treatment- plant capacity assessment, and detailed field verification. In this sense, the model does not replace engineering design; it helps decide where engineering design should begin.

8.3. Limitations

The results should be read against the modelling choices that produced them. It is useful to distinguish between limitations that arise from the input data used in the Larnaka case and limitations that are intrinsic to the simplifying assumptions of the model. The former could be reduced by collecting more complete or more detailed local data; the latter reflect the strategic, planning-level scope of the method and would remain even if more detailed inputs were available.

8.3.1. Data-Related Limitations

Demand representation. Municipal population is distributed across all building footprints in proportion to their area, without distinguishing between residential and non-residential buildings. As a result, part of the resident population is assigned to industrial units, warehouses, retail structures, public buildings, and other non-residential footprints, even though these buildings do not host residents. This affects the spatial demand representation in two ways. First, domestic wastewater demand may be underestimated in genuinely residential areas, because part of the municipal population is allocated to non-residential buildings. Second, non-residential wastewater generation is not represented explicitly. These buildings may generate wastewater through employees, visitors, commercial activity, industrial processes, or other forms of water use, but their contribution should be estimated from land use, occupancy, or water-consumption data rather than from resident population.

The resulting demand layer should therefore be interpreted as a residential-population proxy, not as a complete estimate of wastewater generation. In areas with a high share of large non-residential buildings, the model may distort the local distribution of demand and may underestimate the total wastewater load if non-domestic flows are substantial. A more accurate representation would separate residential demand from non-residential demand: resident population would be allocated only to residential build-

ings, while commercial, industrial, institutional, and public-service wastewater loads would be estimated through building-use information, occupancy assumptions, or measured water-consumption data.

Incomplete infrastructure data. The existing-infrastructure dataset used in the model is spatially incomplete. In particular, no conduit geometries were available for several southern municipalities, including Kiti, Perivolia, and Dromolaxia–Meneou, and the existing pumping-station inventory covers only part of the district. This incompleteness forced several simplifying assumptions in the representation of the brownfield system. The southern system had to be treated as a fully served context, even though service is likely concentrated in the main urban cores rather than being universal. Similarly, the pumping-feasibility screening had to calibrate its gravity-cover threshold on the available sample of existing stations.

These assumptions are reasonable for a strategic planning model, but they simplify the brownfield context and affect the interpretation of the results. Missing conduit geometries may cause existing service areas to be represented too coarsely, while an incomplete pumping-station inventory may affect the calibration of the threshold used to classify new pumping-station candidates. The resulting configurations should therefore be interpreted as planning-level approximations of how the northern and southern systems could interact, not as a complete representation of the existing sewer network.

8.3.2. Method-Intrinsic Limitations

Beyond the data, several limitations follow from the simplifying assumptions of the model itself. These assumptions are consistent with the strategic, planning-level scope of the study, but they also mean that the outputs should be interpreted as planning hypotheses rather than as engineering results.

Dependence on a single treatment endpoint. Every configuration is conditioned on one deterministic WWTP2 location, obtained through a rule-based screening procedure with fixed parameters. Because this single endpoint governs the direction, length, and cost of all generated networks, the whole comparison is conditional on that choice, and no alternative endpoints were evaluated. The direction of the likely effect is nonetheless predictable. Since the endpoint sits near the population-weighted centroid of the northern urban demand, shifting it further north or north-east, closer to Pyla and Kellia, would shorten the trunk connections to the smaller settlements while lengthening those to the main demand mass. This would tend to raise peripheral-municipality coverage under the budgeted heuristics, but at the cost of extra pipe length and, in the flat terrain, probably additional pumping stations toward the core. The reported costs and municipal coverages should therefore be read as conditional on the current endpoint rather than as robust across its plausible range.

A natural extension is to treat the endpoint as a decision variable optimised jointly with the expansion objective. The screening could return a small set of candidate endpoints, and the best one could then be selected per planning priority, since the location that minimises total pipe-and-pumping cost for the efficiency-oriented Shared-trunk logic need not coincide with the one that maximises balanced municipal coverage for the Municipality-targets logic. Choosing an ad hoc endpoint once the objective is fixed would make the treatment endpoint an explicit part of the trade-off analysis rather than a shared upstream assumption, and would let the sensitivity of coverage, cost, and pumping requirements to the endpoint position be quantified rather than only acknowledged.

Simplified cost model and decoupling of pumping from routing. Construction cost is estimated with a single unit rate of 400 EUR/m that is independent of pipe diameter, trench depth, soil conditions, terrain, and construction complexity. In reality, a trunk main conveying the combined northern flow would cost more per metre than a local collector, so the flat rate compresses genuine cost differences between compact and dispersed layouts. Because the budget-constrained configurations all saturate the same pipe-length ceiling, their pipe-only costs are almost identical by construction.

In addition, the pumping-feasibility screening is applied only after the networks have been generated. The routing algorithms minimise pipe length without any direct awareness of where pumping will later be required, and the pumping cost is added afterwards. The model therefore does not co-optimise pipes and pumping. A layout that appears efficient in pipe length may consequently conceal pumping requirements that a more integrated hydraulic-cost formulation would have avoided.

Because every cost result scales linearly with c, the sensitivity of the main conclusions to this parameter

can be assessed directly. At the lower end of the published range, $c = 300$ EUR m^{-1}, the Prim–Steiner full-coverage reference would cost 119.9 M EUR in pipes and 158.9 M EUR including pumping, still above the upper end of the financial envelope; at $c = 500$ EUR m^{-1} it rises to 238.9 M EUR. The conclusion that immediate full urban coverage exceeds the indicated budget is therefore robust across the plausible unit-cost range. For the budget-constrained configurations, the same pipe budget corresponds to $\lambda_{\max}$ between 333 km (at 300 EUR m^{-1}) and 200 km (at 500 EUR m^{-1}): higher unit costs would reduce the achievable coverage within the fixed budget, while lower unit costs would allow the peripheral demand to be reached earlier. The distributional character of the choice between the three budgeted heuristics is unaffected, since all three would continue to saturate the same length ceiling.

Absence of hydraulic and capacity constraints. The model represents pipes and corridors primarily through their spatial geometry, length, and topographic position. It does not explicitly represent pipe diameters, invert levels, capacities, flow directions, flow accumulation, or treatment-endpoint capacity. This is a methodological limitation rather than only a data limitation: the model was designed as a strategic screening tool, not as a hydraulic simulation.

As a result, coverage is topological. A demand node is counted as served once it is connected to the selected network, regardless of whether the downstream pipes, pumping stations, or treatment endpoint could physically convey and treat the additional flow. Similarly, the brownfield reconciliation between WWTP1 and WWTP2 should be understood as a spatial and planning-level allocation, not as an operationally verified hydraulic reassignment. Any transition from the present configurations to an implementable network would require hydraulic modelling of pipe capacities, invert levels, flow directions, pumping requirements, and treatment-plant capacity.

In addition, only the capital cost of new pumping stations is represented in z. The 19–20 stations implied by the budget-constrained configurations would also generate recurring energy and maintenance expenditure over the lifetime of the system [25], which the model does not capture. Including operating costs would further widen the gap between pumping-light and pumping-heavy layouts, and therefore reinforces rather than weakens the conclusion that pumping requirements materially affect configuration affordability in the flat terrain of the district.

Algorithmic simplifications. The network expansion heuristics are designed to make planning trade-offs explicit and comparable, not to guarantee global optimality. The non-budgeted algorithms provide full-coverage references, while the budgeted algorithms explore alternative ways of allocating a fixed pipe-length budget. However, the greedy selection rules used in the budget-constrained configurations may miss combinations of corridors that would perform better globally. Similarly, the Prim–Steiner configuration should be interpreted as a heuristic tree-based reference rather than as a mathematically exact global Steiner optimum.

The magnitude of this limitation can nevertheless be bounded. Since the three budget-constrained heuristics already connect 95.7–97.5% of the modelled urban demand while saturating the same length ceiling, the additional coverage that an exact optimisation could extract from the same budget is at most 2.5–4.3 percentage points. The greedy selection rules may therefore affect the detailed layout of the selected corridors, but they cannot overturn the main comparative conclusions of the configuration analysis.

8.4. Recommendations for Larnaka

The configuration comparison does not point to a single optimal network, but it does provide a clear basis for deciding how the available budget should be used. The main recommendation that follows from the results is that the district should not aim for immediate full urban coverage. Both non-budgeted references exceed the 100 to 150 M EUR envelope, and the cross-family comparison shows that the last few percentage points of coverage are disproportionately expensive, because they require long peripheral extensions and additional pumping stations in flat terrain. A budget-constrained network, which already reaches between 95.7 and 97.5% of the modelled urban demand, is therefore the realistic planning target, and the practical question for Larnaka is not whether to accept a budgeted network, but which budgeted logic to follow within that envelope.

Within the budget, the choice between the three heuristics is essentially a choice of planning priority,

since all three cost almost the same in pipe terms. Shared-trunk maximises the total number of inhabitants connected and is the most appropriate option if the district prioritises aggregate coverage and shared-corridor efficiency. Urban-priority concentrates the same budget on the densest urban clusters, and is more suitable if the immediate goal is to secure the main population centres first. Municipality-targets accepts a small reduction in aggregate coverage, 1.8 percentage points, in exchange for a substantially more balanced distribution across municipalities, raising the coverage of smaller settlements such as Kellia and Pyla that the efficiency-oriented logics leave weakly served.

For the Larnaka case, the results suggest that a municipality-balanced logic, or a hybrid that combines shared-trunk efficiency with a minimum coverage floor for the smaller municipalities, is the most defensible focus for the first investment phase. This is not because it serves the largest number of inhabitants, but because it is the most consistent with the regulatory driver of the project: Directive (EU) 2024/3019 brings agglomerations above 1000 PE within the scope of collective wastewater obligations, and an efficiency-only strategy risks leaving precisely those smaller settlements insufficiently connected. Aligning the first phase with a municipality-balanced logic therefore reduces the risk of building a network that maximises headline coverage while remaining non-compliant for individual agglomerations that the district is legally required to serve.

Finally, the results should be used to define where the network stops rather than only where it extends. Because coverage becomes increasingly expensive at the margin, the district can treat the budget-constrained configurations as a first phase that secures the bulk of the northern demand, and defer the most peripheral connections to a later stage, when additional funding, updated demand data, or a detailed hydraulic assessment become available. Before any of the selected layouts is taken forward, it should be carried into hydraulic modelling and a refined, diameter-differentiated cost assessment that also includes the treatment-plant investment excluded here, so that the strategic direction identified in this thesis is confirmed by engineering-level analysis before implementation.

9

Conclusion

This thesis addressed the wastewater network expansion problem in the northern part of the Larnaka District, where Aradippou, Livadia, Pyla, Kellia, and Oroklini remain unserved or only partially served by collective wastewater infrastructure. Under Directive (EU) 2024/3019, the reduction of the mandatory collection-and-treatment threshold from 2,000 to 1,000 PE strengthens the need for a technically plausible and financially realistic expansion strategy. At the same time, the available sewer-network budget, the flat coastal terrain, the incomplete brownfield data, and the likely need for pumping infrastructure make full immediate coverage difficult to achieve.

Against this background, the thesis developed a spatial graph-based planning approach to generate and compare wastewater network expansion configurations under cost, coverage, existing-infrastructure, and pumping-feasibility constraints. The main research question was:

How can a spatial graph-based planning approach be used to create, assess, and compare wastewater network expansion configurations for the northern part of the Larnaka District under cost, coverage, existing-infrastructure, and pumping-feasibility constraints?

9.1. Answer to the Research Questions

The main research question was addressed through a five-phase modelling workflow, with each phase corresponding to one research sub-question: baseline graph construction, treatment-endpoint positioning, network expansion and brownfield allocation, pumping-feasibility screening, and configuration comparison.

The first sub-question concerned the construction of a baseline spatial graph. This thesis showed that the wastewater expansion problem can be represented through a graph that combines road-based construction corridors, building-footprint-based demand, municipal population, stakeholder-provided conduits and pumping stations, and terrain elevation. Population was disaggregated to buildings by footprint area, aggregated to road nodes, and filtered to a modelled urban terminal set of 109,129 inhabitants, only 1.0% below the total positive population represented in the model. This confirmed that a planning-level graph can represent the relevant spatial elements of the wastewater expansion problem while explicitly distinguishing between demand, candidate corridors, existing assets, and terrain.

The second sub-question concerned the positioning of the northern treatment endpoint. A rule-based screening procedure was used to define WWTP2 as a planning-level root node for the expansion configurations. The procedure combined restriction to admissible municipalities, clearance from the urban footprint, northward geographic preference, road-node snapping, and low-elevation filtering. It reduced 3,909 geographic candidates to 392 low-elevation candidates and finally to a single WWTP2 root node. This made the treatment endpoint an explicit modelling assumption rather than an implicit fixed input. At the same time, the selected endpoint should be interpreted as a strategic location for configuration comparison, not as a permitted or hydraulically verified wastewater treatment plant site.

The third sub-question concerned the generation of network expansion configurations and the allocation

of existing assets between WWTP1 and WWTP2. Five heuristics were developed: two non-budgeted full-coverage references, Rooted Dijkstra and Prim–Steiner, and three budget-constrained alternatives, Shared-trunk, Urban-priority, and Municipality-targets. All five generated layouts were verified to be connected to WWTP2 and acyclic, with a cyclomatic number of zero. The generated networks were then reconciled with the existing brownfield infrastructure. This reconciliation raised the WWTP2 population share from a raw 26.6–29.7% to a final 45.5–46.7%, and allocated 13 of the 22 existing pumping stations to the northern system. This demonstrated that a defensible two-system interpretation cannot be obtained from new-pipe routing alone: it also requires an explicit reinterpretation of the existing sewer assets.

The fourth sub-question concerned pumping-feasibility screening. The generated and corrected networks were screened using terrain information and a gravity-cover threshold calibrated from the available existing pumping-station data, with $\delta_{\max} = 8.63$ m. The screening identified between 18 and 30 retained pumping-station candidates per configuration, most of which were classified as mandatory. This result confirmed that, in the flat terrain of the Larnaka District, pumping is not a marginal detail. Pipe-only cost systematically understates the investment required to implement the network layouts.

The fifth sub-question concerned configuration comparison and planning recommendations. The five configurations were evaluated in terms of population coverage, pipe length, total cost, cost per inhabitant served, pumping requirements, WWTP1/WWTP2 allocation, and municipal distribution. The comparison revealed two main trade-offs: full coverage versus financial realism, and aggregate efficiency versus municipal balance.

Taken together, these phases answer the main research question. A spatial graph-based planning approach can be used to create, assess, and compare wastewater network expansion configurations for the northern Larnaka service area by integrating demand representation, corridor-based routing, treatment-endpoint definition, existing-infrastructure interpretation, pumping-feasibility screening, and configuration evaluation within one coherent framework. Its value is not that it produces a single optimal sewer layout, but that it makes the main planning trade-offs explicit before detailed engineering design begins.

Three results are central. First, the planning-level model can generate full-urban-coverage configurations, but their estimated capital cost exceeds the indicated budget. The more compact full-coverage reference, Prim–Steiner, requires 399.8 km of new pipe and reaches EUR 198.9 million once pumping is included, EUR 48.9 million above the upper end of the budget envelope. Second, a budget-constrained first phase can already serve 95.7–97.5% of the modelled urban demand at a total cost of EUR 127.0–130.0 million including pumping-station CAPEX. Third, because the three budget-constrained configurations saturate the same pipe-length ceiling and have almost identical total costs, the choice between them is mainly distributional rather than economic. It determines whether investment maximises aggregate coverage, concentrates on dense urban clusters, or deliberately improves coverage in smaller municipalities such as Pyla and Kellia.

9.2. Scientific Contribution

The scientific contribution of this thesis is best understood in relation to the separate strands of literature reviewed in Chapter 2. Wastewater service-configuration studies explain how settlement density, distance, scale, and governance affect the choice between centralised, decentralised, and hybrid systems [4]. They do not, however, directly determine how distributed demand within a partially served district should be connected through a specific collection network. This thesis operationalises that spatial planning problem by translating municipal demand into graph terminals and by evaluating alternative corridor-based expansion configurations for a defined northern service area.

A second strand of literature provides graph-based representations of street networks and general routing methods [16], [20], [21]. These methods establish how spatial connectivity and shortest paths can be represented computationally, but they do not by themselves incorporate wastewater demand, treatment endpoints, existing sewer assets, municipal coverage objectives, or pumping-related consequences. The framework developed here adapts this graph logic to wastewater planning by combining road-based construction corridors, demand-weighted nodes, a treatment root, and distinguishable existing and proposed infrastructure within one spatial model.

A third strand concerns tree-based and constrained network design [22], [23]. This thesis does not claim a new exact optimisation algorithm. Its contribution is instead to use contrasting shortest-path, tree-growth, path-aware, cluster-based, and municipality-targeted heuristics as explicit representations of different planning priorities. Their comparison demonstrates that configurations with similar aggregate cost and coverage can have substantially different municipal distributions. The addition of σ_x and $x^{\min}$ makes this distributional consequence measurable rather than leaving it as a qualitative map interpretation.

The hydraulic and pumping literature emphasises that sewer feasibility depends on gradient, excavation depth, and pumping infrastructure [5], [19], [25]. Such work commonly addresses detailed design or operation once the network structure is known. The present study contributes a planning-level bridge between spatial routing and later hydraulic design: terrain-derived gravity-cover screening is applied to each generated configuration, and the retained pumping candidates are incorporated into the capital-cost comparison. This does not replace hydraulic modelling, but it prevents pipe length from being treated as the sole indicator of technical and financial plausibility.

Finally, the literature recognises both the distributional character of urban water investment [6], [24] and the importance of existing assets in long-lived infrastructure systems. The framework combines these concerns through municipal coverage indicators and an explicit brownfield-reconciliation step between WWTP1 and WWTP2. The resulting scientific contribution is therefore an integrated, planning-level workflow for partially served districts: it connects spatial demand, corridor-based routing, alternative budget-allocation logics, brownfield interpretation, municipal distribution, and pumping-aware cost assessment before construction-ready hydraulic information is available.

The contribution lies in this integration and operationalisation, rather than in any single component. It addresses the research gap identified in Section 2.6 by showing how methods that are usually treated separately can be assembled into a transparent and verifiable decision-support framework. The Larnaka application demonstrates the framework, while its phase-based structure and explicit local parameters make clear which elements can be transferred and which require recalibration in another partially served district.

9.3. Societal Contribution

The societal contribution of this thesis lies in supporting a wastewater infrastructure decision that affects public health, environmental protection, regulatory compliance, and the distribution of essential services across the Larnaka District. Collective wastewater infrastructure is not only a technical system: it determines which communities gain access to safer sanitation, how environmental risks from inadequate onsite systems are reduced, and how public investment is distributed between larger urban centres and smaller settlements.

In this context, the thesis provides a transparent evidence base for understanding the consequences of different wastewater expansion strategies. Rather than treating full coverage as an abstract objective, the analysis shows what full urban coverage would cost, how much of the northern demand can be served within the available budget, and which communities remain less well covered under different prioritisation logics. This makes the social consequences of infrastructure phasing more explicit.

The results show that immediate full urban coverage should not be treated as the first investment target, because the final few percentage points of coverage require disproportionate additional pipe length and pumping infrastructure. A budget-constrained first phase is therefore more realistic and can already serve most of the modelled northern urban demand. From a societal perspective, this matters because it supports a more feasible use of public resources while still expanding collective wastewater service to a large share of the currently unserved or partially served population.

At the same time, the results show that maximising aggregate coverage is not automatically the most socially defensible choice. Because Directive (EU) 2024/3019 concerns individual agglomerations above 1,000 PE, a strategy that performs well in total coverage terms may still leave smaller municipalities insufficiently connected. For this reason, a municipality-balanced strategy, or a hybrid strategy that combines shared-trunk efficiency with minimum municipal coverage floors, appears more defensible than a purely efficiency-oriented expansion. This is especially relevant for settlements such as Pyla

and Kellia, where the distributional effects of the budget-constrained heuristics are most visible.

The broader societal value of the framework is therefore its ability to make infrastructure trade-offs visible before implementation. It clarifies not only how much a network may cost, but also who is served, who may remain excluded, and how different investment logics affect the fairness and regulatory adequacy of wastewater service provision. The model does not replace engineering design, but it helps ensure that the next design phase starts from a transparent understanding of the social and spatial consequences of the available choices.

9.4. Directions for Future Research

Several directions could extend the work developed in this thesis.

First, future research should introduce a temporal dimension into the model by coupling the expansion workflow with demographic projections. The current model is static and evaluates all configurations against a single population snapshot based on the 2021 Census. A projection-based version would allow each candidate network to be tested against future demand over a multi-decade planning horizon. This would make it possible to assess whether a layout that is efficient under current conditions remains robust if demand shifts, if municipalities such as Pyla and Kellia grow faster than the urban core, or if new development emerges along the proposed corridors. The objective would therefore move from selecting a network that is optimal for one population snapshot to identifying configurations that remain reliable under demographic uncertainty.

Second, the framework should be tested in other partially served districts. Although the workflow was designed as a transferable planning approach, it has only been demonstrated on the Larnaka case. Applying it to districts with different terrain, brownfield infrastructure completeness, settlement patterns, or treatment configurations would help evaluate its generality. Such comparisons would clarify which components are broadly reusable and which require local recalibration, such as the treatment-endpoint screening rules, the urban-footprint thresholds, the cost assumptions, or the pumping-feasibility calibration.

Third, future work should broaden the set of algorithmic logics used to generate expansion configurations. This thesis compared five heuristics representing full coverage, shared-corridor efficiency, urban concentration, and municipal balance. Additional logics could prioritise environmental sensitivity, regulatory compliance under Directive (EU) 2024/3019, or explicit equity criteria across municipalities. A more advanced extension would replace or complement the greedy heuristics with exact or metaheuristic optimisation, such as integer programming or multi-objective optimisation. This would make it possible to quantify the optimality gap of the current heuristics and generate a Pareto frontier between coverage, cost, pumping requirements, and municipal balance.

Finally, before any proposed layout is considered for implementation, the preferred configuration should be developed through detailed engineering analysis. This would require hydraulic modelling of pipe capacities, invert levels, flow directions, pumping requirements, and treatment-plant capacity, together with field verification and a refined cost estimate that includes the treatment-plant investment excluded from this thesis.

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A

Appendix A - AI Statement

Generative artificial intelligence tools, namely ChatGPT and Claude, were used during the preparation of this thesis as auxiliary support tools. Their use was limited to two main purposes: coding support and writing support.

For the coding component, AI tools were used to assist with the drafting, organisation, debugging, and refinement of Python code used in the modelling workflow. This included support for spatial data processing, graph construction, network expansion algorithms, pumping-feasibility screening, verification checks, and the generation of tables and visual outputs. All code produced or modified with AI assistance was reviewed, adapted, tested, and interpreted by the author.

For the written component, AI tools were used to improve the clarity, grammar, structure, and academic formulation of draft text. The tools supported the editing and refinement of the thesis, but did not replace the author's judgement in defining the research problem, selecting the methodology, interpreting the results, or formulating the conclusions.

B

Appendix B - Code Repository

The code developed for this thesis is available in a dedicated GitHub repository:

`https://github.com/lmariglianodelft/Appendix-B---Wastewater-Network-Expansion-Optimisation-in-the-Larnaka-District-Cyprus-.git`

The repository contains the main computational files used to implement the spatial graph-based wastewater network expansion workflow for the Larnaka District case study. These files document the modelling steps used for the non-budgeted configurations, the budget-constrained configurations, the correction and brownfield-reconciliation stage, and the pumping-feasibility screening. HTML exports of the same files are provided to make the code and outputs directly accessible from a web browser. The repository also includes the code used to generate additional figures and the complete maps of all network configurations developed in the study.

The repository is intended to support transparency of the computational workflow rather than full standalone reproducibility. Some auxiliary datasets and intermediate GIS files are not publicly redistributed because they include stakeholder-provided wastewater infrastructure data and manually processed case-study materials. As a result, the code can be inspected through the repository, but the complete workflow cannot be rerun without access to the full original input-data chain.

C

Appendix C - Verification and Validation

This appendix documents the verification and validation checks introduced in Section 6.7. The checks are organised by modelling phase and follow the same order as the methodology. Verification checks confirm that each step of the workflow behaves as intended. The existing pumping-station dataset provides local empirical calibration and a limited plausibility check for the pumping-feasibility screening, but should not be interpreted as independent validation because the same evidence is used during parameterisation.

C.1. Phase 1: Baseline Graph Construction

Municipal boundary plausibility. The nine municipal boundaries retrieved from OpenStreetMap were checked for plausible area and centroid location. All areas fall within the expected range for the district, from 8.50 km^2 (Perivolia) to 55.90 km^2 (Aradippou), with no degenerate or empty geometries. One geocoding failure was detected and handled: the query for Perivolia did not return a polygon and the workflow fell back to the alternative spelling, which returned a valid boundary. A dedicated check on Livadia confirmed that the retrieved geometry was correct rather than an unintended larger polygon.

Population conservation. The building-level population allocation of Equation 6.1 was verified to conserve the municipal population totals w_m. For every municipality, the population aggregated over all building footprints reproduces the input municipal population exactly, as shown in Table C.1. The total assigned population equals 110,260 inhabitants with no leakage, confirming that the disaggregation and re-aggregation steps preserve the demand mass.

Building-footprint plausibility. The building layer was screened for municipalities with implausibly few footprints. The automatic check for municipalities with fewer than 100 buildings returned an empty set, and all nine municipalities were found to contain buildings, for a total of 49,717 footprints after cleaning. This confirms that the Microsoft footprint tiles were correctly downloaded, clipped, and assigned to municipalities.

Demand-to-road snapping. The snapping of building demand to road-graph nodes was verified through the distribution of snapping distances. Across the 49,717 demand buildings, the mean snapping distance is 28.8 m and the median is 23.9 m, with a maximum of 383 m. The largest snapping distances correspond almost exclusively to peripheral buildings carrying negligible assigned population, on the order of one inhabitant or less, and therefore do not materially affect the demand representation. Existing-asset snapping was checked in the same way: 5,668 sewer nodes were matched to road nodes with a mean distance of 11.6 m, and all 6,379 existing conduits were successfully linked to road-node endpoints at both ends.

Table C.1: Population conservation check. For every municipality, the assigned population reproduces the input population exactly.

Municipality	Population input	Population assigned
Larnaka	52,046	52,046
Aradippou	22,932	22,932
Livadia	8,581	8,581
Oroklini	7,575	7,575
Dromolaxia–Meneou	6,838	6,838
Kiti	5,136	5,136
Perivolia	3,920	3,920
Pyla	2,845	2,845
Kellia	387	387
Total	110,260	110,260

C.2. Phase 2: WWTP2 Endpoint Positioning

The selected root node r was verified to satisfy every screening rule in Table 6.2. The candidate lies in the admissible northern area, respects the minimum clearance from the urban footprint (170.7 m against a 150 m minimum), and lies 161.7 m north of the minimum admissible northing. It is also represented within the road graph in accordance with the snapping-distance requirement.

The geographic screening retained 3,909 candidates, of which 392 remained after the low-elevation filter. The selected node has a ground elevation of 45.17 m, below the low-elevation eligibility threshold of 60.34 m, and has the minimum final site score within the retained subset. The node belongs to the dominant road-graph component, ensuring that the subsequent expansion algorithms can route to it. DEM sampling over the candidate set was effectively complete, with a missing rate of 0.1% or below.

C.3. Phase 3: Network Expansion and Brownfield Allocation

Connectivity to the root. Every generated network configuration was checked for connectivity to the WWTP2 root r. In the two non-budgeted configurations, 7,482 of the 7,483 required terminals are represented in the root-connected layout. The single exception is an isolated terminal in Pyla located on a disconnected road-graph fragment and carrying approximately 0.1 inhabitants. The three budget-constrained configurations are partial-coverage configurations by design; all nodes included in their selected layouts are connected to r and no disconnected selected fragments remain.

Acyclicity and duplicate-corridor verification. The topology of each generated new-pipe layout was verified using the cyclomatic number

$$\mu = |E'| - |N'| + \kappa, \tag{C.1}$$

where E' is the set of selected new-pipe edges, N' is the set of nodes incident to those edges, and κ is the number of connected components. For each of the five configurations, the selected layout contains one connected component and satisfies $\mu = 0$. The root is present in every layout, all selected nodes are reachable from the root, and the number of pipe records equals the number of distinct undirected corridors. Table C.2 reports the complete check.

These results confirm that all five layouts are trees rooted at WWTP2. Visual line crossings or closely parallel corridors in the maps therefore do not represent topological loops.

Budget compliance. The three budget-constrained networks were verified to respect the length ceiling $\lambda_{\max} = 250$ km derived from the budget. Their realised new-pipe lengths are 249.99 km for Shared-trunk, 249.93 km for Urban-priority, and 249.96 km for Municipality-targets, each below the ceiling, with corresponding pipe costs of approximately 99.97–99.99 M EUR. The budget constraint is therefore satisfied in every budget-constrained configuration.

Table C.2: Connectivity, acyclicity, and duplicate-corridor verification for the five generated new-pipe layouts.

Configuration	$\lvert N' \rvert$	$\lvert E' \rvert$	κ	μ	Nodes not draining to r	Duplicate corridors
Rooted Dijkstra	15,829	15,828	1	0	0	0
Prim–Steiner	13,774	13,773	1	0	0	0
Shared-trunk	9,136	9,135	1	0	0	0
Urban-priority	9,531	9,530	1	0	0	0
Municipality-targets	9,564	9,563	1	0	0	0

Manual reconciliation consistency. The manual brownfield reconciliation was checked for internal consistency. Of the nodes exported for manual review, 334 were reclassified as already covered. The consistency check confirms that no node manually excluded as already covered simultaneously remains flagged as requiring new network: the corresponding set is empty. This verifies that the manual correction step produced a spatially and logically coherent classification without contradictory assignments.

C.4. Phase 4: Pumping-Feasibility Screening

Verification. The DEM sampling used in the gravity-cover screening was checked for completeness over the road-graph nodes, with a missing rate at or below 0.1% and the missing values handled by local interpolation. The minimum-slope value derived from Manning's equation for the representative design pipe was checked against the parameters reported in Table 5.4. The implementation was also checked to distinguish the 1.75 m raw-candidate detection threshold from the subsequent mandatory and optional retention rules described in Table 6.4.

Local empirical calibration and plausibility check. The maximum admissible gravity cover depth was calibrated from the recorded depths of the 22 existing pumping stations. The resulting 90th-percentile value is 8.63 m and is adopted as $\delta_{\max}$. The candidate-classification logic also uses terrain and network contexts derived from the existing stations, including a median local relief of 12.5 m and an upper-quartile relief of 15.8 m. Candidates arising in comparable contexts can therefore be retained as mandatory.

This calibration ties the feasibility screening to the depth range and terrain contexts in which pumping has historically been required in the district and provides a limited plausibility check on the retained candidates. Because the same existing-station dataset contributes to both parameterisation and subsequent interpretation, the procedure is not an independent validation. It also does not validate pipe capacities, flow directions, invert levels, pump sizes, or treatment-endpoint capacity, none of which are represented at this planning level.

C.5. Summary

Table C.3 consolidates the checks. Taken together, they confirm that the workflow behaves as intended at every phase, that the demand mass is conserved, that all selected new-pipe layouts are connected and acyclic, that the budget-constrained configurations satisfy their length ceiling, and that the pumping screening is grounded in observed local data. Full validation of the hydraulic behaviour of a preferred configuration lies beyond the planning-level scope of this study and is identified as future work in Chapter 8.

Table C.3: Summary of verification and validation checks by phase.

Phase	Check	Outcome
Phase 1	Municipal boundary area and geometry	All plausible; one geocoding fallback handled
Phase 1	Population conservation against w_m	Exact; total 110,260, no leakage
Phase 1	Building-footprint plausibility	No municipality below 100 buildings; 49,717 total
Phase 1	Demand-to-road snapping	Mean 28.8 m; large distances limited to negligible population
Phase 1	Existing-asset snapping	6,379 of 6,379 conduits linked at both ends
Phase 2	Endpoint admissibility and clearance	All rules satisfied; selected elevation 45.17 m
Phase 2	Connectivity to dominant graph component	Confirmed
Phase 3	Selected-layout connectivity to r	Confirmed for all five configurations; no selected orphan nodes
Phase 3	Acyclicity and duplicate-corridor check	All five configurations have $\mu = 0$ and no duplicate corridors
Phase 3	Budget compliance $\ell(E') \leq \lambda_{\max}$	Satisfied in all three budget-constrained configurations
Phase 3	Manual reconciliation consistency	No contradictory node assignments
Phase 4	DEM sampling completeness	Missing rate $\leq 0.1\%$
Phase 4	$\delta_{\max}$ calibration and plausibility check	Calibrated from existing stations; P90 $= 8.63$ m; not independent validation