

Positioning grids at critical locations for the design of water distribution network

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EECOS
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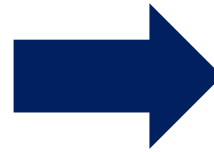
1 | INTRODUCTION



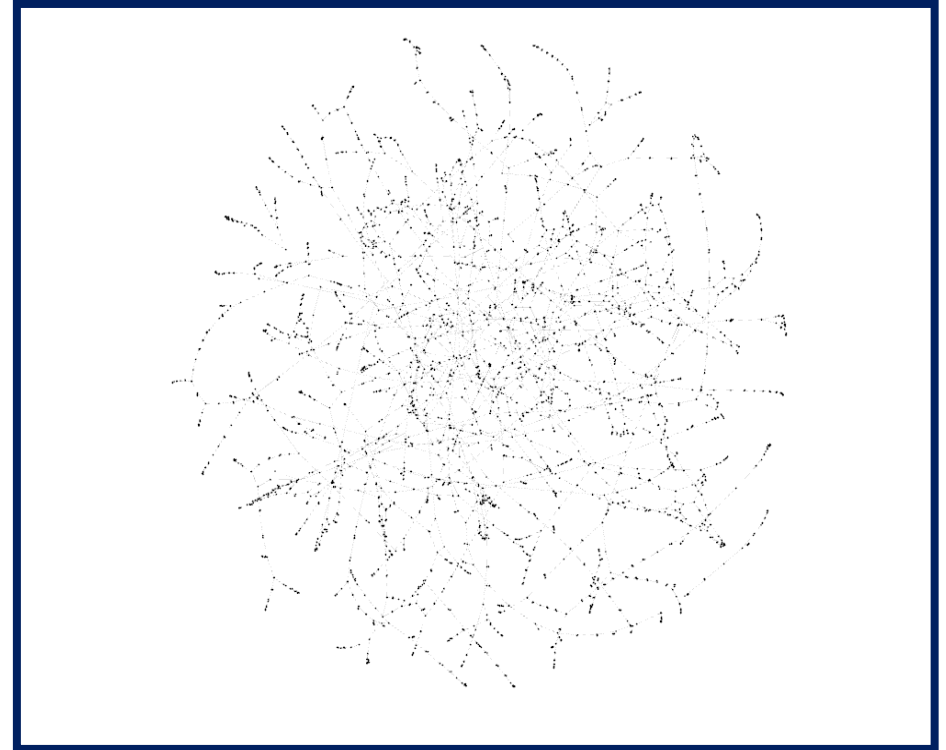
1.1. Network science

- Water distribution system can be modeled as a two-dimensional complex network consisting of vertices (nodes) and pipes (edges)

Water distribution systems (WDSs)



Water distribution networks (WDNs)



1 | INTRODUCTION

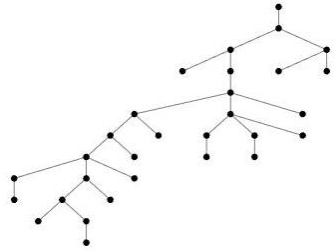
1.1. Network science



Properties of WDNs

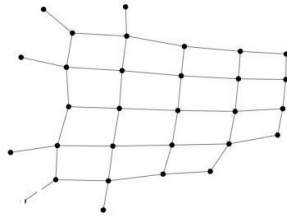
(Son et al. 2021)

Tree network



No loops
No alternative path

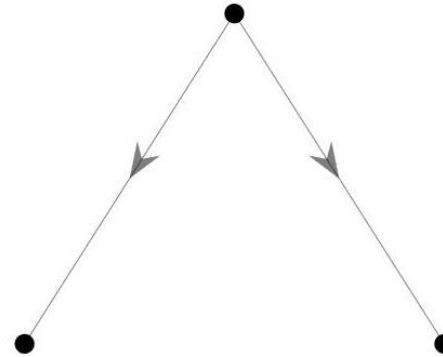
Lattice network



Planar grids

- Composed of lattice and tree proportion in two-dimension

Source

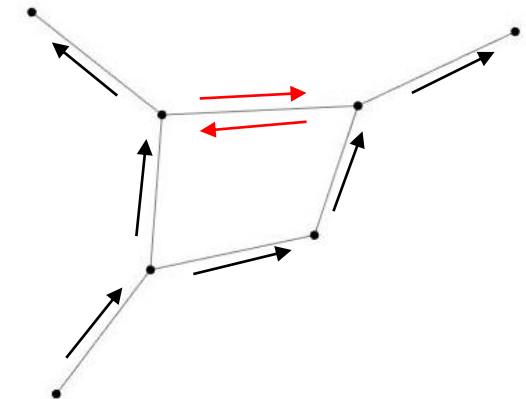


Demand

Demand

- Existence of source and demand with general direction

Demand



Source

Demand

- Non-fixed direction in loops

WDNs are primal undirected network that intersections are nodes and pipes are edges.

1 | INTRODUCTION



1.2. Backgrounds and Objectives

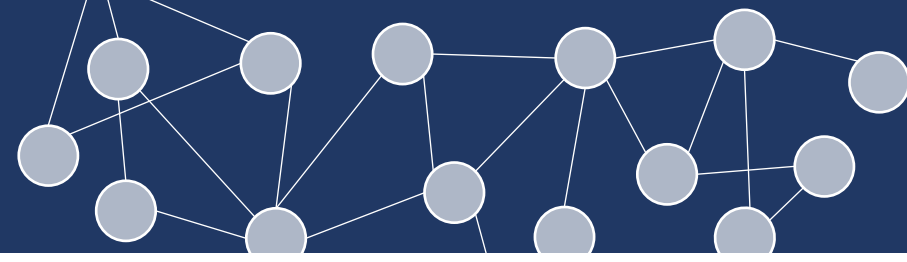
Backgrounds

- A water distribution network (WDN) is a critical and life-line infrastructure that transports and distributes water, an essential resource for human life, to local communities.
- The system function of the WDNs should always remain at a reliable state.

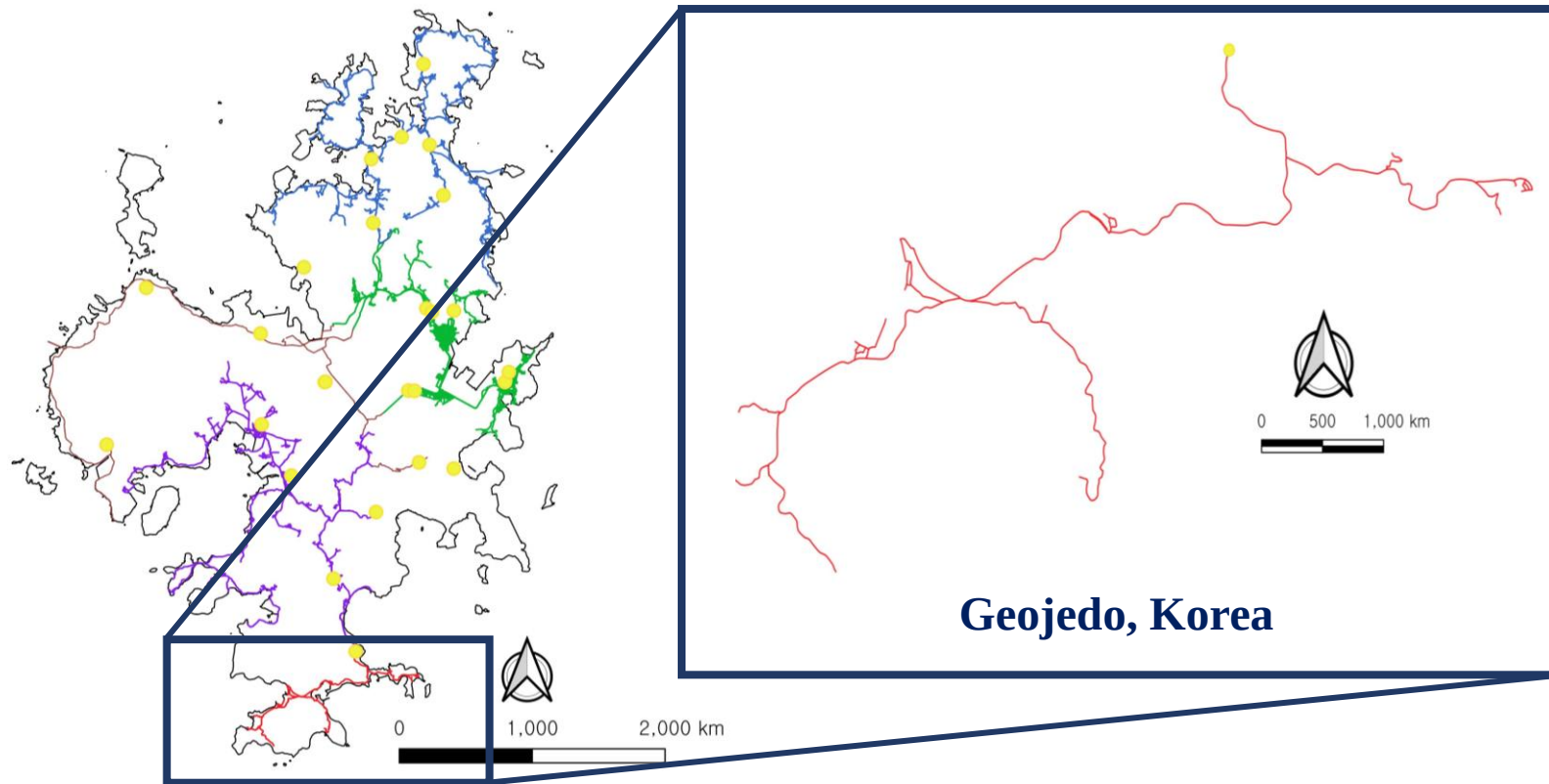
Objectives

- Assess the system function (e.g. Efficiency) of study case by a random network model.
- Identify critical locations regarding the extent of increments of function for locating new grids.
- Propose an optimal (or suboptimal) design of WDNs considering spatial network characteristics.

2 | STUDY AREA



Geojedo	# of nodes (n) (Intersects)	# of edges (m) (Pipes)	# of sources (s) (Water distributor)	# of demands (d) (Households)
South	137	150	1	19



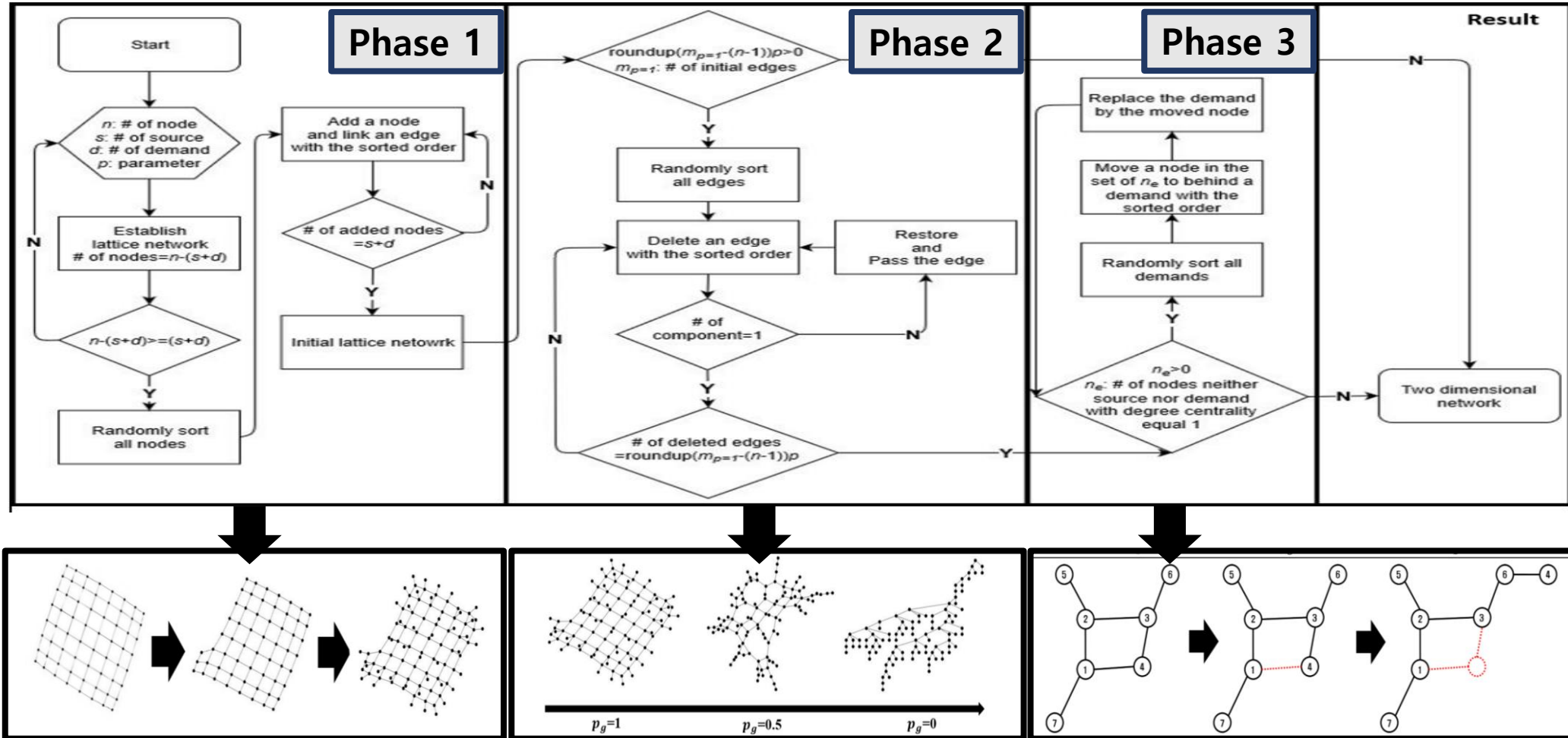
- A primal undirected network with a single source

3 METHODS



3.1. The Lattice to Tree Network Model (LTNM)

- To obtain mean properties and their variation, the networks were randomly generated with the aid of a Monte Carlo simulation.



3 | METHODS

3.1. The Lattice to Tree Network Model (LTNM)



The process to establish the networks with p_g (example network)

Grid Ratio

$$p_g = \frac{m(p_g) - (n-1)}{m_{p_g=1} - (n-1)}$$

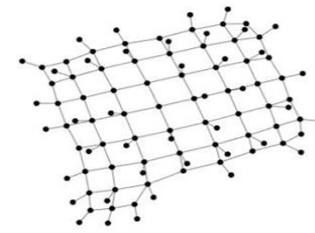
$$(0 \leq p_g \leq 1)$$

Number of constituents :

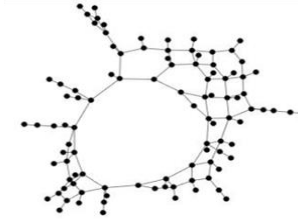
Node (n) : 640

Source (s) : 1

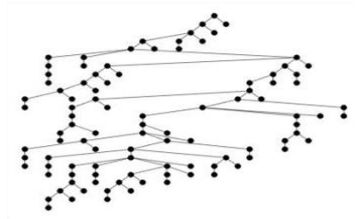
Demand (d) : 139



$p_g=1$



$p_g=0.5$

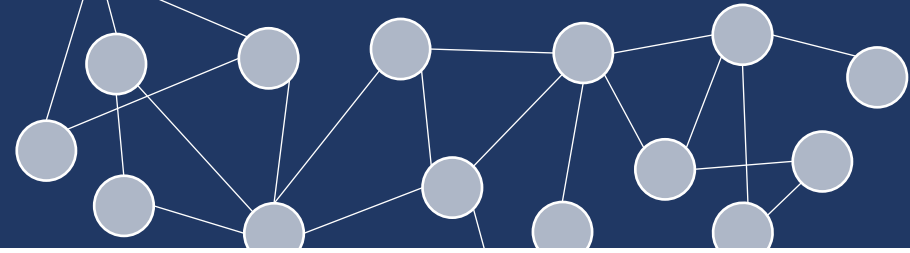


$p_g=0$

p_g	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
n	640	640	640	640	640	640	640	640	640	640	640
m	639	684	730	775	821	866	912	957	1003	1048	1095

- The number of edges at p_g : $m(p_g) = m_{p_g=0} + p_g(m_{p_g=1} - (n - 1))$, $m_{p_g=0} \leq m(p_g) \leq m_{p_g=1}$
- The total number of node is constant : $n(p_g) = n_{p_g=0} = n_{p_g=1} = n$
- $k \times l$ square lattice network with source and demand, $m_{p_g=1} \cong 2kl - k - l + (s + d)$
- $m_{p_g=0} = n_{p_g=1} - 1$ (Mej 2010; Caldarelli 2007)

3 | METHODS



3.2. Metrics

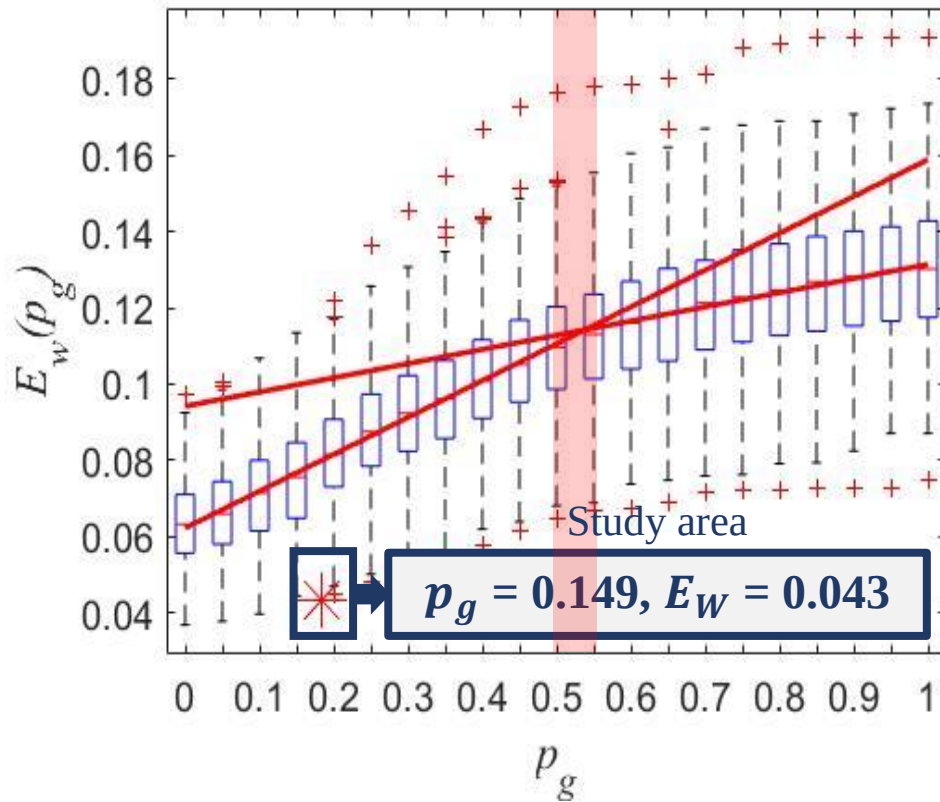
Metric	Definition	Equation	Quantifying
Degree Centrality	The number of links adjacent to a node i (Yazdani and Jeffrey, 2012)	$k_i = \sum_j x_{ij}$ x_{ij} : number of lines between nodes i and j	Robustness
Clustering Coefficient	The ratio of the number of closed triples $3N_{\Delta}$ (N_{Δ} is the number of triangles) to the number of connected triples of vertices N_3 (Yazdani et al., 2011)	$c = \frac{3N_{\Delta}}{N_3}$	Centrality
Average path length	The average shortest distance d (i.e. the minimum number of links from one node to the other) between any pair of nodes v_i and v_j (Yazdani et al., 2011)	$L = \frac{1}{n(n-1)} \times \sum_{i,j=1}^n d(v_i, v_j)$	Efficiency
Efficiency	The average of reciprocal of shortest path lengths between all pairs of nodes (Cedex 2008), but, in here, between source and demand nodes.	$E_w(G) = \frac{1}{n_s n_d} \sum_{i \in s, j \in d} \frac{1}{d(i, j)}$ n_s : # of source nodes n_d : # of demand nodes $d(i, j)$: Shortest path length between nodes i and j	Efficiency

4 Results

4.1 Effects of p

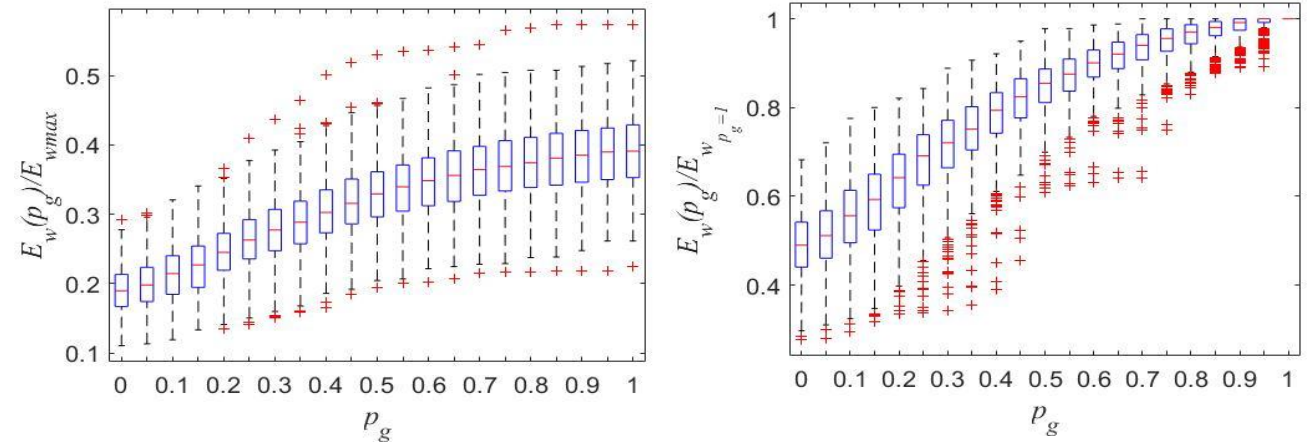


Boxplot of Efficiency (E_w)
(n:137, s:1, d:19)



⊗ Monte Carlo simulation with 500 realizations.

Boxplot of normalized Efficiency



- Efficiency increases non-linearly with the increase of grid proportion.
- The threshold around 0.538 was obtained by SLR method.
- **Since the study area also has p below the threshold, the functioning of system can be improved by increasing grid proportion.**

p_g threshold : 0.538, $E_w = 0.111$

4 | RESULTS

4.2 Increasing p_g by adding Edge

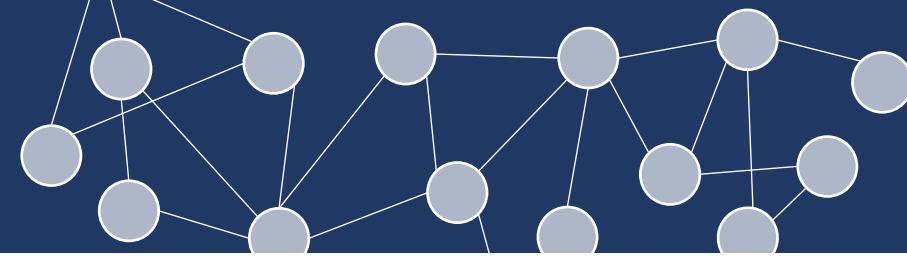
p_g can be improved by adding edges

Exclude edges that are directly connected to demand nodes and source nodes
(Degree needs to be remain 1)



- A total of 6,656 connectable edges exist.
- The degree centrality of one node in the water distribution network is not greater than 4 when connecting a new edge (maximum node degree centrality in WDNs is limited by spatial characteristics (Giustolis et al., 2017))
- **Add edges in order of the critical locations that increases efficiency the most when located.**

Initial network : $p_g = 0.149$, $E_W = 0.043$



Efficiency improvement when adding each edges

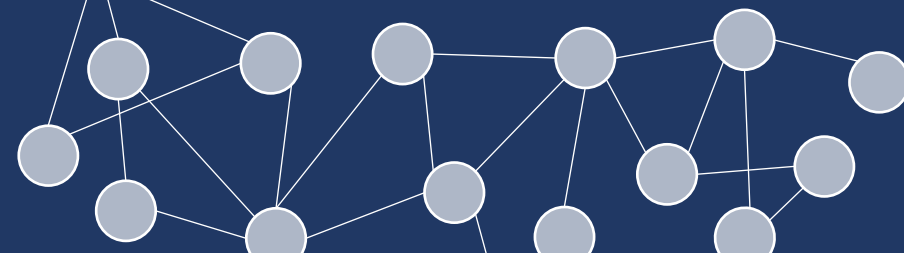
No	node1	node2	Efficiency
1	9	96	0.097
2	11	96	0.095
3	13	96	0.094
4	12	96	0.091
5	15	96	0.088

...

6655	134	136	0.043
6656	134	137	0.043

4 RESULTS

4.2 Increasing p_g by adding Edge

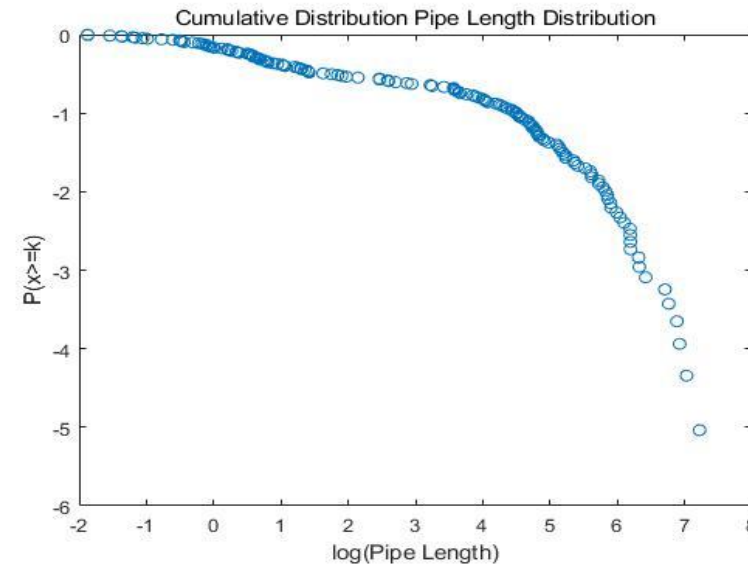


Edge Forwarding – not considering distance

No	node1	node2	Efficiency	Distance(m)
1	9	96	0.097	6117.8
2	126	96	0.132	3189.2
3	63	98	0.154	3156.1
4	90	98	0.168	2074.8
5	13	26	0.176	1448.5
6	11	47	0.183	2191.7
7	106	124	0.190	947.8
8	84	97	0.195	4022.6
9	7	97	0.201	5824.8
10	76	127	0.206	4435.6
11	127	133	0.211	150.8
12	88	91	0.213	125.5
13	15	34	0.215	1123.7
14	133	137	0.216	39.3
15	2	5	0.218	494.5

<Pipe lengths of southern part of Geojeodo>

- Maximum length of pipes : 2617m
- Minimum Length of pipes : 0.15m
- Average Length of pipes : 149.78m
- **Most of the length of water pipes are less than 500m.**



- **Should consider Geographic and topographic factors of the study area**

4 RESULTS



4.2 Increasing p_g by adding Edge

	Original Network	Added edges less than 500m	Added edges less than 1km	Added edges less than 1.5km	Added edges less than 2km
# of edge※	150	173	173	168	170
Average node Degree	2.19	2.53	2.53	2.45	2.48
c	0.056	0.100	0.072	0.061	0.058
L	18.19	10.06	8.05	7.45	6.32
E_W	0.043	0.086	0.114	0.150	0.177
p_g	0.146	0.385	0.385	0.333	0.355

※ The minimum number of edges corresponding to the maximum achievable Efficiency in each length condition (see Appendix)

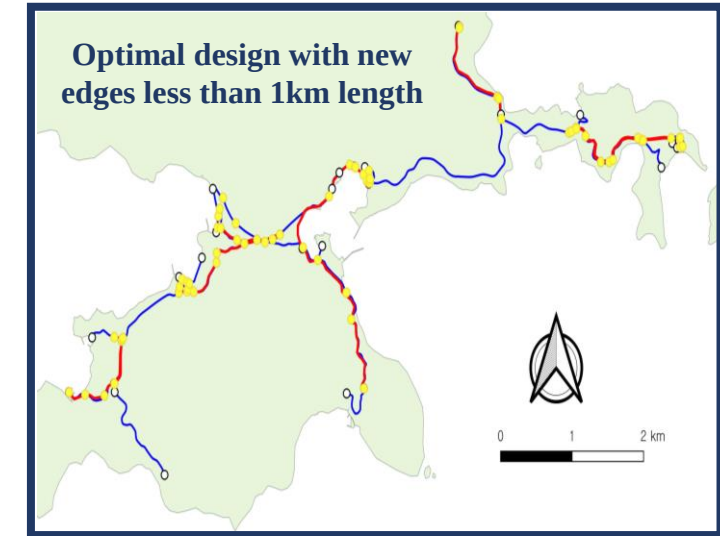
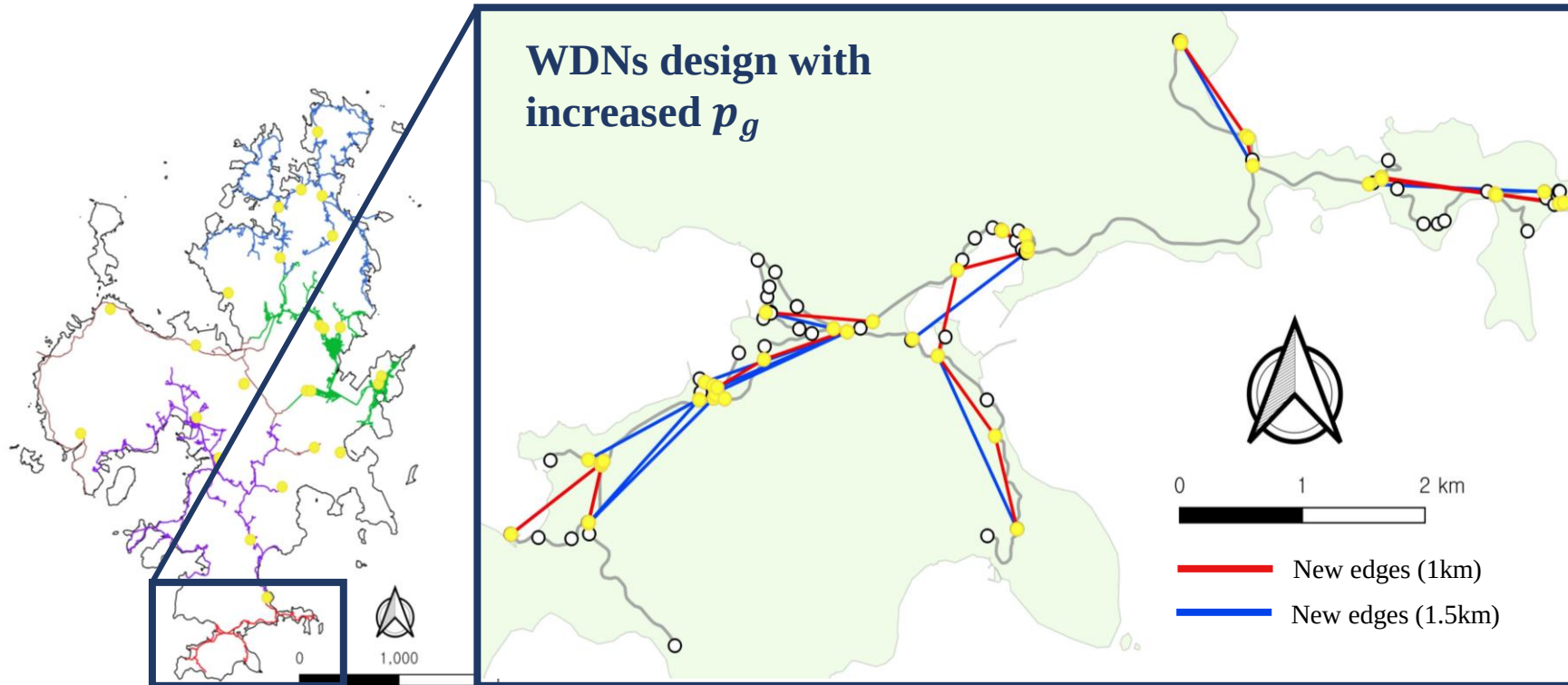
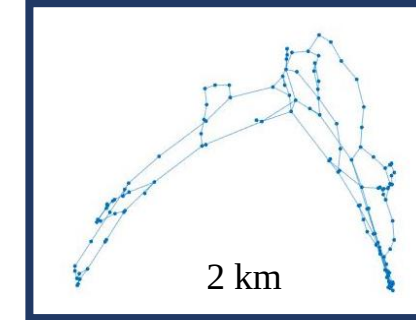
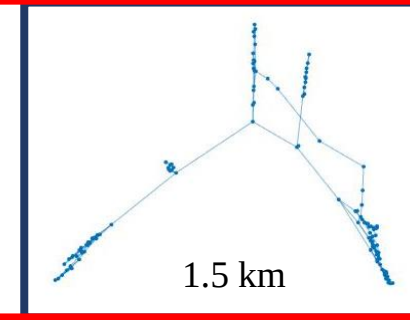
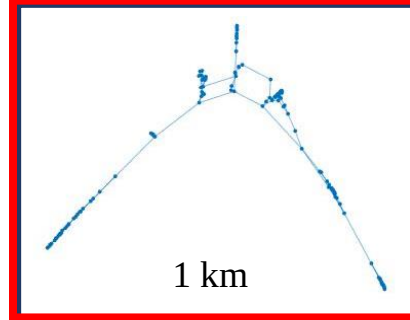
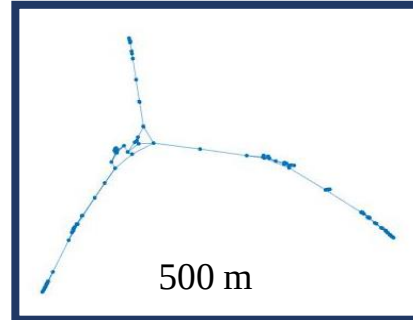
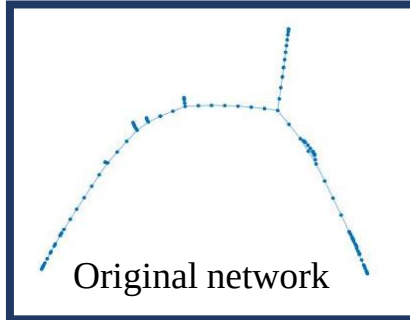
- The network characterizes small world network as the limit of attached pipe length increases.
- There were no changes in Efficiency after further increase in Grid ratio.
- The performance of WDNs which originally had low grid ratios are improved by adding pipes less than 1km and 1.5km at crucial locations.

4 RESULTS

4.3 Optimal design of WDNs

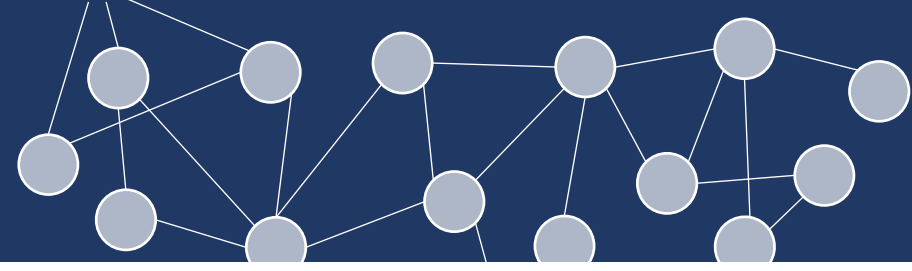


Structural changes in WDNs



- Can be more specific with topographic factors of study area

5 | CONCLUSION



- 1) A threshold exists and the networks with low efficiency can be improved by adjusting p_g .
- 2) The range of functions varies depending on where grids are located at a fixed grid ratio.
- 3) Spatial characteristics need to be considered when locating new edges.
- 4) These approaches give a new framework for improving the structure and function of existing WDNs.
- 5) Need to include more details (e.g., size of pipes, installation costs, water policies).

Thank you

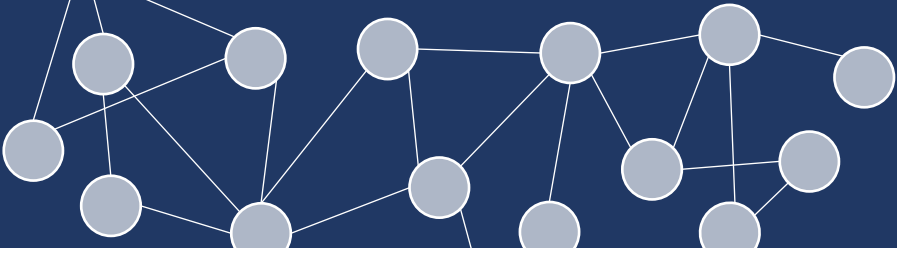
Acknowledgements

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APPENDIX

Increasing p by adding Edge– Forwarding by distance



Adding edges less than - 2km				
No	node1	node2	Efficiency	Distance(m)
1	88	96	0.0647	1974.9
2	62	92	0.0863	1184.0
3	96	106	0.1018	1951.3
4	106	126	0.1255	1332.4
5	21	58	0.1391	1317.3
6	76	94	0.1456	247.7
7	107	133	0.1518	1463.4
8	41	58	0.1558	680.9
9	9	17	0.1596	479.4
10	34	63	0.1632	1815.9
11	74	94	0.1667	1503.4
12	2	20	0.1685	1861.0
13	26	57	0.1698	1225.2
14	74	84	0.1711	748.6
15	133	137	0.1723	39.3
16	90	93	0.1736	40.4
17	7	20	0.1746	1020.4
18	12	29	0.1757	1409.3
19	57	76	0.1766	1487.4
20	11	25	0.1772	1453.1

Adding edges less than 1.5km				
No	node1	node2	Efficiency	Distance(m)
1	96	103	0.0643	1136.0
2	62	91	0.0840	1160.4
3	104	126	0.1014	1431.0
4	21	58	0.1149	1317.3
5	104	106	0.1202	114.7
6	106	133	0.1249	1463.5
7	41	58	0.1289	680.9
8	76	93	0.1329	248.5
9	9	17	0.1368	479.4
10	63	84	0.1402	1499.5
11	34	57	0.1424	1146.0
12	26	57	0.1442	1225.2
13	88	93	0.1455	91.2
14	2	16	0.1467	928.4
15	7	20	0.1477	1020.4
16	12	20	0.1488	1319.7
17	133	137	0.1497	39.3
18	11	29	0.1503	1412.8

Adding edges less than 1km				
No	node1	node2	Efficiency	Distance(m)
1	99	103	0.0512	238.3
2	96	99	0.0590	911.4
3	111	124	0.0672	944.1
4	66	91	0.0747	591.0
5	39	60	0.0822	934.9
6	63	66	0.0890	688.1
7	104	106	0.0930	114.7
8	34	39	0.0964	439.7
9	76	93	0.0996	248.5
10	41	60	0.1021	875.1
11	9	17	0.1042	479.4
12	126	133	0.1063	151.5
13	21	35	0.1076	207.5
14	64	74	0.1087	781.2
15	88	93	0.1096	91.2
16	26	35	0.1105	208.3
17	123	137	0.1113	564.2
18	2	16	0.1121	928.4
19	106	120	0.1127	935.6
20	118	133	0.1133	528.1
21	74	84	0.1138	748.6
22	12	16	0.1140	480.4
23	7	18	0.1143	125.0