ಕರ್ನಾಟಕ ವಿಧಾನ ಪರಿಷತ್ತು

1. ಚುಕ್ಕೆ ಗುರುತಿಲ್ಲದ ಪ್ರಶ್ನೆ ಸಂಖ್ಯೆ : 1222
2. ಸದಸ್ಯರ ಹೆಸರು : ಶ್ರೀ . ಕೆ.ಎ. ತಿಪ್ಪೇಸ್ವಾಮಿ
3. ಉತ್ತರಿಸ ಬೇಕಾದ ದಿನಾಂಕ : 19.12.2024
4. ಉತ್ತರಿಸುವ ಸಚಿವರು : ಮಾನ್ಯ ಸಣ್ಣ ನೀರಾವರಿ, ವಿಜ್ಞಾನ ಮತ್ತು ತಂತ್ರಜ್ಞಾನ ಸಚಿವರು

ಕ್ರ.ಸಂ	ಪ್ರಶ್ನೆ	ಉತ್ತರ
ಅ	ಬೆಂಗಳೂರು ನಗರದಲ್ಲಿರುವ ಕಣಿವೆಗಳು ಯಾವುವು; ಮತ್ತು ಈ ಕಣಿವೆಗಳ ವ್ಯಾಪ್ತಿಯಲ್ಲಿ ಬರುವ ಕೆರೆಗಳು ಯಾವುವು; (ಈ ಬಗ್ಗೆ ಪೂರ್ಣ ಮಾಹಿತಿ ನೀಡುವುದು).	ಬೆಂಗಳೂರು ನಗರ ಜಿಲ್ಲೆಯ ವ್ಯಾಪ್ತಿಯಲ್ಲಿ ಕಾವೇರಿ ಹಾಗೂ ದಕ್ಷಿಣ ಪಿನಾಕಿನಿ ಕಣಿವೆಗಳು ಬರುತ್ತವೆ. ಈ ಕಣಿವೆಗಳ ವ್ಯಾಪ್ತಿಯಲ್ಲಿ ಒಟ್ಟು 78 ಸಣ್ಣ ನೀರಾವರಿ ಕೆರೆಗಳು ಇರುತ್ತವೆ, (ಕೆರೆವಾರು,ಕಣಿವೆವಾರು ವಿವರಗಳನ್ನು ಅನುಬಂಧ-1 ರಲ್ಲಿ ನೀಡಲಾಗಿದೆ)
ಆ	ಬೆಂಗಳೂರು ನಗರದ ಕಲುಷಿತ ನೀರನ್ನು ಶುದ್ಧೀಕರಿಸಿ ಯಾವ ಯಾವ ಕಣಿವೆಗಳ ಮುಖೇನಾ ನಗರದ ಪಕ್ಕದ ಜಿಲ್ಲೆಗಳಲ್ಲಿನ ಕೆರೆಗಳನ್ನು ತುಂಬಿಸಲು ಯೋಜನೆಗಳನ್ನು ರೂಪಿಸಲಾಗಿದೆ; ಮತ್ತು ಈ ಯೋಜನೆಗಳ ಅನುಷ್ಠಾನ ಯಾವ ಹಂತದಲ್ಲಿವೆ; (ಈ ಬಗ್ಗೆ ಪೂರ್ಣ ಮಾಹಿತಿ ನೀಡುವುದು).	ಬೆಂಗಳೂರು ನಗರದ ಕೆ.ಸಿ ವ್ಯಾಲಿ, ಹೆಚ್.ಎನ್ ವ್ಯಾಲಿ ಮತ್ತು ವೃಷಭಾವತಿ ವ್ಯಾಲಿಗಳಿಂದ ಬರುವ ತ್ಯಾಜ್ಯ ನೀರನ್ನು ಬೆಂಗಳೂರು ನೀರು ಸರಬರಾಜು ಮತ್ತು ಒಳಚರಂಡಿ ಮಂಡಳಿಗಳ ತ್ಯಾಜ್ಯ ನೀರು ಸಂಸ್ಕರಣಾ ಘಟಕಗಳಿಂದ ದ್ವಿತೀಯ ಹಂತದಲ್ಲಿ ಸಂಸ್ಕರಿಸಿದ ತ್ಯಾಜ್ಯ ನೀರನ್ನು ಪಡೆದು ಬೆಂಗಳೂರು ನಗರದ ಪಕ್ಕದ ಜಿಲ್ಲೆಗಳಾದ ಕೋಲಾರ, ಚಿಕ್ಕಬಳ್ಳಾಪುರ, ಬೆಂಗಳೂರು ಗ್ರಾಮಾಂತರ, ತುಮಕೂರು ಜಿಲ್ಲೆಗಳ ಕೆರೆಗಳಿಗೆ ತುಂಬಿಸಲು ಸಣ್ಣ ನೀರಾವರಿ ಇಲಾಖೆ ವ್ಯಾಪ್ತಿಯಲ್ಲಿ 7 ಏತ ನೀರಾವರಿ ಯೊಜನೆಗಳನ್ನು ರೂಪಿಸಲಾಗಿದ್ದು, ಯೋಜನೆಗಳ ಅನುಷ್ಠಾನದ ಹಂತ, ಸದರಿ ಯೋಜನೆಗಳಿಗೆ ನಿಗದಿಪಡಿಸಲಾದ ಅನುದಾನ ಹಾಗೂ ವೆಚ್ಚದ ವಿವರಗಳನ್ನು ಅನುಬಂಧ - 2 ರಲ್ಲಿ ನೀಡಲಾಗಿದೆ.
ಇ	ರಾಜ್ಯ ಸರ್ಕಾರ ಈ ಯೋಜನೆಗಳಿಗೆ ನಿಗಧಿಪಡಿಸಿದ ಒಟ್ಟು ಅನುದಾನವೆಷ್ಟು; ಮತ್ತು ಇದುವರೆಗೂ ಎಷ್ಟು ಅನುದಾನವನ್ನು ಬಳಸಿಕೊಳ್ಳಲಾಗಿದೆ; (ಈ ಬಗ್ಗೆ ಪೂರ್ಣ ಮಾಹಿತಿ ನೀಡುವುದು).	
ಈ	ರಾಜ್ಯ ಸರ್ಕಾರ ಕಲುಷಿತ ನೀರನ್ನು ಶುದ್ಧಿಕರಿಸಿ ನಾಗರೀಕರು ಮತ್ತು ರೈತರು ಉಪಯೋಗಿಸುವುದರಿಂದ ಈ ಬಗ್ಗೆ ಉಂಟಾಗುವ ಹಾನಿಕಾರಕ ವಿಷಯಗಳ ಬಗ್ಗೆ ಸರ್ಕಾರ ಅಧ್ಯಯನ ನಡೆಸಿದೆಯೇ; ಹಾಗಿದ್ದಲ್ಲಿ ಅಧ್ಯಯನದಿಂದ ಹೊರ ಹೊಮ್ಮಿದ ವಿಷಯಗಳು ಯಾವುವು? (ಈ ಬಗ್ಗೆ ಪೂರ್ಣ ಮಾಹಿತಿ ನೀಡುವುದು).	ಸದರಿ ಯೋಜನೆಗಳಿಂದ ತುಂಬಿಸಲಾಗುತ್ತಿರುವ ದ್ವಿತೀಯ ಹಂತದಲ್ಲಿ ಸಂಸ್ಕರಿಸಿದ ತ್ಯಾಜ್ಯ ನೀರನ್ನು ಕೆರೆಗಳಿಗೆ ತುಂಬಿಸಿ ಅಂತರ್ಜಲ ಮರುಪೂರಣ ಮಾಡಲು ಉದ್ದೇಶಿಸಲಾಗಿದ್ದು, ನಾಗರೀಕರಿಗೆ ಹಾಗೂ ರೈತರಿಗೆ ನೇರವಾಗಿ ಉಪಯೋಗಿಸಲು ಅವಕಾಶವಿರುವುದಿಲ್ಲ. ಈ ಕುರಿತು ಭಾರತೀಯ ವಿಜ್ಞಾನ ಸಂಸ್ಥೆಯ ರವರಿಂದ ಪರಿಸರ ಅಘಾಧಿಕರಣ ಅಧ್ಯಯನ ಮಾಡುತ್ತಿದ್ದು, ಈ

		ಅಧ್ಯಯನದಿಂದ ತಿಳಿದುಬಂದಿರುವ ಕೆಲವು ಅಂಶಗಳು ಈ ಕೆಳಗಿನಂತಿವೆ: • ದ್ವಿತೀಯ ಹಂತದಲ್ಲಿ ಸಂಸ್ಕರಿಸಿದ ತ್ಯಾಜ್ಯ ನೀರು NGT 2019 ಮಾನದಂಡಗಳನ್ನು ಪೂರೈಸುತ್ತದೆ. • ದ್ವಿತೀಯ ಹಂತದಲ್ಲಿ ಸಂಸ್ಕರಿಸಿದ ತ್ಯಾಜ್ಯ ನೀರಿನ ಗುಣಮಟ್ಟವನ್ನು ದ್ವಿತೀಯ ಹಂತದಲ್ಲಿ ಸಂಸ್ಕರಿಸಿದ ತ್ಯಾಜ್ಯ ನೀರಿನಿಂದ ಮರುಪೂರಣಗೊಂಡ ಕೊಳವೆ ಬಾವಿಯ ನೀರು ಹಾಗೂ ಮಳೆ ನೀರಿನಿಂದ ಮರುಪೂರಣಗೊಂಡ ಕೊಳವೆ ಬಾವಿಯ ನೀರಿನೊಂದಿಗೆ ಹೋಲಿಸಿದಾಗ, ಗುಣಮಟ್ಟದಲ್ಲಿ ವ್ಯತ್ಯಾಸ ಕಂಡುಬಂದಿರುವುದಿಲ್ಲ. • ಅಧ್ಯಯನ ಕೈಗೊಂಡ ಬೆಳೆಗಳನ್ನು ವಿವಿಧ ಜಲಗಳೊಂದಿಗೆ ನೀರಾವರಿ ಮಾಡಿದಾಗ, ಭೂಮಿಯ ಗುಣಲಕ್ಷಣಗಳಲ್ಲಿ ಅಥವಾ ಕೃಷಿ ಸೂಚಕಗಳಲ್ಲಿ ಗಮನೀಯ ವ್ಯತ್ಯಾಸಗಳು ಕಂಡುಬಂದಿರುವುದಿಲ್ಲ. • ದ್ವಿತೀಯ ಹಂತದಲ್ಲಿ ಸಂಸ್ಕರಿಸಿದ ತ್ಯಾಜ್ಯ ನೀರಿನಿಂದ ಬೆಳೆಯಲಾದ ಬೆಳೆಗಳ ಇಳುವರಿಯಲ್ಲಿ ಯಾವುದೇ ವ್ಯತ್ಯಾಸವನ್ನು ಗಮನಿಸಲಾಗಿರುವುದಿಲ್ಲ. • ಬೇರೆ ನೀರಿನೊಂದಿಗೆ ಬೆಳೆಯುವ ಬೆಳೆಗಳಂತೆ ದ್ವಿತೀಯ ಹಂತದಲ್ಲಿ ಸಂಸ್ಕರಿಸಿದ ತ್ಯಾಜ್ಯ ನೀರಿನಿಂದ ಬೆಳೆಯಲಾದ ಬೆಳೆಗಳೂ ಸಹ ದೀರ್ಘ ಕಾಲದ ವರೆಗೆ ತಾಜಾತನದಿಂದ ಇರುತ್ತವೆ. ಪ್ರಸ್ತುತ ಹಂತದ ವರದಿಯನ್ನು ಅನುಬಂಧ-3 ರಲ್ಲಿ ನೀಡಲಾಗಿದೆ.

ಕಡತ ಸಂಖ್ಯೆ: MID 139 LCQ 2024

(ಎನ್.ಎಸ್ ಭೋಸರಾಜು)
ಸಣ್ಣ ನೀರಾವರಿ, ವಿಜ್ಞಾನ ಮತ್ತು
ತಂತ್ರಜ್ಞಾನ ಸಚಿವರು

ವಿಧಾನ ಪರಿಷತ್ತಿನ ಸದಸ್ಯರಾದ ಶ್ರೀ.ಕೆ.ಎ ತಿಪ್ಪಸ್ವಾಮಿ (ನಾಮನಿರ್ದೇಶನ ಹೊಂದಿದವರು) ರವರ ಚುಕ್ಕೆ ಗುರುತಿಲ್ಲದ ಪ್ರಶ್ನೆ ಸಂಖ್ಯೆ: 1222ಗೆ

ಅನುಬಂಧ-1

ಬೆಂಗಳೂರು ನಗರ ಜಿಲ್ಲೆಯಲ್ಲಿರುವ ಕಣಿವೆಗಳ ವಿವರಗಳು

SL.NO	DISTRICT	TALUK	NAME OF TANK	BASIN
1	BANGAORE URBAN	ANEKAL	ANEKAL DODDA KERE	SOUTH PENNAR
2	BANGAORE URBAN	ANEKAL	ANEKAL RAJAN KERE	SOUTH PENNAR
3	BANGAORE URBAN	ANEKAL	ARE HALLI DODDA KERE	SOUTH PENNAR
4	BANGAORE URBAN	ANEKAL	BIDARAGERE DODDA KERE	SOUTH PENNAR
5	BANGAORE URBAN	ANEKAL	BIDARAGUPPE AMANI KERE	SOUTH PENNAR
6	BANGAORE URBAN	ANEKAL	BOMMASANDRA KERE	SOUTH PENNAR
7	BANGAORE URBAN	ANEKAL	AMANI BIDARAGERE	SOUTH PENNAR
8	BANGAORE URBAN	ANEKAL	GUTTAHALLI BOMMANA KERE	SOUTH PENNAR
9	BANGAORE URBAN	ANEKAL	HARAGADDE DODDA KERE	SOUTH PENNAR
10	BANGAORE URBAN	ANEKAL	HENNAGARA AMANI KERE	SOUTH PENNAR
11	BANGAORE URBAN	ANEKAL	HULIMANGAL DODDA KERE	SOUTH PENNAR
12	BANGAORE URBAN	ANEKAL	HUSKUR KERE	SOUTH PENNAR
13	BANGAORE URBAN	ANEKAL	JIGANI DODDA KERE	SOUTH PENNAR
14	BANGAORE URBAN	ANEKAL	KARPURA KERE	SOUTH PENNAR
15	BANGAORE URBAN	ANEKAL	MARSUR DODDA KERE	SOUTH PENNAR
16	BANGAORE URBAN	ANEKAL	MAYASANDRA DODDA KERE	SOUTH PENNAR
17	BANGAORE URBAN	ANEKAL	MUGALURU KODI KERE	SOUTH PENNAR
18	BANGAORE URBAN	ANEKAL	MUTHANALLUR AMANI KERE	SOUTH PENNAR
19	BANGAORE URBAN	ANEKAL	PANDITANA AGRAHARA KERE	SOUTH PENNAR
20	BANGAORE URBAN	ANEKAL	SAKALAVAR BHUJANGADASAN	SOUTH PENNAR
21	BANGAORE URBAN	ANEKAL	SARJAPURA DODDA KERE	SOUTH PENNAR
22	BANGAORE URBAN	ANEKAL	SARJAPURA CHIKKA KERE	SOUTH PENNAR
23	BANGAORE URBAN	ANEKAL	SINGENA AGRAHARA TANK	SOUTH PENNAR
24	BANGAORE URBAN	BANGAORE SOUTH	URAMUNDINAKERE	SOUTH PENNAR
25	BANGAORE URBAN	BANGAORE SOUTH	HARALUR KERE	SOUTH PENNAR
26	BANGAORE URBAN	BANGAORE SOUTH	SONNANAHALLI KERE	SOUTH PENNAR
27	BANGAORE URBAN	BANGAORE SOUTH	KAYAM GUNTE	SOUTH PENNAR
28	BANGALORE URBAN	BANGAORE SOUTH	MAUJIKERE	SOUTH PENNAR
29	BANGAORE URBAN	BANGAORE SOUTH	AREKERE MATTIKERE	SOUTH PENNAR
30	BANGAORE URBAN	BANGAORE SOUTH	ITTALURU KERE	SOUTH PENNAR
31	BANGAORE URBAN	BANGAORE SOUTH	HOSAKERE	SOUTH PENNAR
32	BANGAORE URBAN	BANGAORE SOUTH	KALENA AGRAHARA KERE	SOUTH PENNAR
33	BANGAORE URBAN	BANGAORE SOUTH	KAMMANAHALLI CHIKKAKERE	SOUTH PENNAR
34	BANGAORE URBAN	BANGAORE SOUTH	KANISANDRA KERE	SOUTH PENNAR
35	BANGAORE URBAN	BANGAORE SOUTH	BASAVAPURA KERE	SOUTH PENNAR
36	BANGAORE URBAN	ANGAORE EAST/SOUT	BELLANDUR AMMANI KERE	SOUTH PENNAR
37	BANGAORE URBAN	BANGAORE EAST	GUNJUR URAMUNDINAKERE	SOUTH PENNAR

SL.NO	DISTRICT	TALUK	NAME OF TANK	BASIN
38	BANGAORE URBAN	BANGAORE EAST	CHOULAKERE	SOUTH PENNAR
39	BANGAORE URBAN	BANGAORE EAST	KODATHI DODDAKERE	SOUTH PENNAR
40	BANGAORE URBAN	BANGAORE EAST	SULAKUNTE DEVARA KERE	SOUTH PENNAR
41	BANGAORE URBAN	BANGAORE EAST	SADARAMANGALA GRAMADA K	SOUTH PENNAR
42	BANGAORE URBAN	BANGAORE EAST	PASALAREDDY KERE	SOUTH PENNAR
43	BANGAORE URBAN	BANGAORE EAST	NELLORAHALLI KERE	SOUTH PENNAR
44	BANGAORE URBAN	BANGAORE EAST	MULLURU KERE	SOUTH PENNAR
45	BANGAORE URBAN	BANGAORE EAST	MARALAKERE	SOUTH PENNAR
46	BANGAORE URBAN	BANGAORE EAST	MAUJI KERE	SOUTH PENNAR
47	BANGAORE URBAN	BANGAORE EAST	KODIKERE/MAUJIKERE	SOUTH PENNAR
48	BANGAORE URBAN	BANGAORE EAST	URAMUNDINAKERE	SOUTH PENNAR
49	BANGAORE URBAN	BANGAORE EAST	KODAGIKERE	SOUTH PENNAR
50	BANGAORE URBAN	BANGAORE EAST	HONALA KERE	SOUTH PENNAR
51	BANGAORE URBAN	BANGAORE EAST	HUDIGIDDANA KERE	SOUTH PENNAR
52	BANGAORE URBAN	BANGAORE EAST	HARALAKUNTE KERE	SOUTH PENNAR
53	BANGAORE URBAN	BANGAORE EAST	KUNDARAHALLI KERE	SOUTH PENNAR
54	BANGAORE URBAN	BANGAORE EAST	KAYAM GUNTE	SOUTH PENNAR
55	BANGAORE URBAN	BANGAORE EAST	MADYADA KERE	SOUTH PENNAR
56	BANGAORE URBAN	ANEKAL	BAGGINA DODDA KERE	CAUVERY
57	BANGAORE URBAN	ANEKAL	BOMMANDA HALLI KERE	CAUVERY
58	BANGAORE URBAN	ANEKAL	BYATARAYANA DODDI KERE	CAUVERY
59	BANGAORE URBAN	YELAHANKA	SRIRAMANAHALLI KERE	CAUVERY
60	BANGAORE URBAN	YELAHANKA	SURADENAPURA YEKKANAKERI	CAUVERY
61	BANGAORE URBAN	YELAHANKA	NELLAKUNTE KERE	CAUVERY
62	BANGAORE URBAN	YELAHANKA	CHELLIHALLI KERE	CAUVERY
63	BANGAORE URBAN	YELAHANKA	DIBBURU KERE	CAUVERY
64	BANGAORE URBAN	YELAHANKA	SURADHENUPURA DODDAKERE	CAUVERY
65	BANGAORE URBAN	YELAHANKA	BHUDAMARANAHALLI KERE	CAUVERY
66	BANGAORE URBAN	YELAHANKA	HANIYUR	CAUVERY
67	BANGAORE URBAN	YELAHANKA	KARALAPURA	CAUVERY
68	BANGAORE URBAN	YELAHANKA	KAKOLA ITTIKERE	CAUVERY
69	BANGAORE URBAN	YELAHANKA	KOLAVARAYANAHALLI KERE	CAUVERY
70	BANGAORE URBAN	YELAHANKA	KUMBARAHALLI KERE	CAUVERY
71	BANGAORE URBAN	YELAHANKA	KALATHAMMANAHALLI KERE/URAMUNDINAKERE	CAUVERY
72	BANGAORE URBAN	BANGALORE NORTH	GUDDADAHALLI KERE	CAUVERY
73	BANGAORE URBAN	BANGAORE SOUTH	NAGANAIKANAHALLI	CAUVERY
74	BANGAORE URBAN	BANGAORE SOUTH	VADDARAKERE	CAUVERY
75	BANGAORE URBAN	BANGAORE SOUTH	RAMAPPANAKERE	CAUVERY
76	BANGAORE URBAN	BANGAORE SOUTH	MANGAMMA PALYAKERE	CAUVERY
77	BANGAORE URBAN	BANGAORE SOUTH	PALYADAKERE	CAUVERY
78	BANGAORE URBAN	BANGAORE EAST	PALYAKERE	CAUVERY

ವಿಧಾನ ಪರಿಷತ್ತಿನ ಸದಸ್ಯರಾದ ಶ್ರೀ/ಶ್ರೀಮತಿ ಕೆ.ಎ ತಿಪ್ಪಸ್ವಾಮಿ (ನಾಮನಿರ್ದೇಶನ ಹೊಂದಿದವರು) ರವರ ಚುಕ್ಕೆ ಗುರುತಿನ /ಗುರುತಿಲ್ಲದ ಪ್ರಶ್ನೆ ಸಂಖ್ಯೆ: 1222ಕ್ಕೆ ಅನುಬಂಧ–2

ಬೆಂಗಳೂರು ನಗರದ ದ್ವಿತೀಯ ಹಂತದಲ್ಲಿ ಸಂಸ್ಕರಿಸಿದ ತಾಜ್ಯ ನೀರನ್ನು ಏತ ನೀರಾವರಿ ಮೂಲಕ ಕೆರೆ ತುಂಬಿಸುವ ಯೋಜನೆಗಳ ವಿವರಗಳು

(ರೂ.ಲಕ್ಷಗಳಲ್ಲಿ)

ಕ್ರ ಸಂ.	ಜಿಲ್ಲೆ	ತಾಲ್ಲೂಕು	ಕಾಮಗಾರಿಯ ಹೆಸರು	ಅಂದಾಜು ಮೊತ್ತ	ವೆಚ್ಚ	ಷರಾ
1	2	3	4	5	6	7
1	ಬೆಂಗಳೂರು ನಗರ	ಆನೇಕಲ್	ಬೆಂಗಳೂರು ನಗರ ಕೆ ಮತ್ತು ಸಿ ವ್ಯಾಲಿಯ ಸಂಸ್ಕರಣಾ ಘಟಕದಿಂದ ಸಂಸ್ಕರಿಸಿದ ತ್ಯಾಜ್ಯ ನೀರನ್ನು ಏತ ನೀರಾವರಿ ಮೂಲಕ ಆನೇಕಲ್ ತಾಲ್ಲೂಕಿನ 67–ಕೆರೆಗಳನ್ನು ಹಾಗೂ ಕನಕಪುರ ತಾಲ್ಲೂಕಿನ ರಾವುತನಹಳ್ಳ ಮತ್ತು ಮಾವತ್ತೂರು ಕೆರೆಗಳನ್ನು ತುಂಬಿಸುವ ಕಾಮಗಾರಿ.	24000.00	23110.12	ಕಾಮಗಾರಿ ಪ್ರಗತಿಯಲ್ಲಿರುತ್ತದೆ.
2	ಬೆಂಗಳೂರು ಗ್ರಾಮಾಂತರ	ಹೊಸಕೋಟೆ	ಬೆಂಗಳೂರು ಗ್ರಾಮಾಂತರ ಜಿಲ್ಲೆ, ಹೊಸಕೋಟೆ ತಾ: 30+8 ಕೆರೆಗಳಿಗೆ ಕೆ.ಆರ್.ಪುರಂ.ಎಸ್.ಟಿ.ಪಿ.(ವೆಂಗಯ್ಯನಕೆರೆ) ಯಿಂದ ಸಂಸ್ಕರಿಸಿದ ತ್ಯಾಜ್ಯ ನೀರನ್ನು ತುಂಬಿಸುವ ಏತ ನೀರಾವರಿ ಯೋಜನೆ ನಿರ್ಮಾಣ ಕಾಮಗಾರಿ	9350.00	3914.25	ಕಾಮಗಾರಿ ಪೂರ್ಣಗೊಂಡಿದ್ದು ನಿರ್ವಹಣೆ ಕಾಮಗಾರಿ ಪ್ರಗತಿಯಲ್ಲಿರುತ್ತದೆ.
3	ಕೋಲಾರ	ಕೋಲಾರ ಮಾಲೂರು ಬಂಗಾರಪೇಟೆ ಮುಳಬಾಗಿಲು ಶ್ರೀನಿವಾಸಪುರ ಮತ್ತು ಚಿಂತಾಮಣಿ	ಬೆಂಗಳೂರು ನಗರ ಸಂಸ್ಕರಿಸಿ ಕೊಳಚೆ ನೀರನ್ನು ಕೋಲಾರ ಜಿಲ್ಲೆಯ ಹಾಗೂ ಚಿಕ್ಕಬಳ್ಳಾಪುರ ಜಲ್ಲೆಯ ಚಿಂತಾಮಣಿ ತಾಲ್ಲೂಕಿನ ಒಟ್ಟು 126 ಕೆರೆಗಳಿಗೆ ತುಂಬಿಸುವ ಏತ ನೀರಾವರಿ ಯೋಜನೆಯ ಕಾಮಗಾರಿ	145000.00	142639.53	ಕಾಮಗಾರಿ ಪೂರ್ಣಗೊಂಡಿದ್ದು ನಿರ್ವಹಣೆ ಕಾಮಗಾರಿ ಪ್ರಗತಿಯಲ್ಲಿರುತ್ತದೆ.
4	ಕೋಲಾರ	ಕೋಲಾರ ಮಾಲೂರು ಬಂಗಾರಪೇಟೆ ಮುಳಬಾಗಿಲು ಶ್ರೀನಿವಾಸಪುರ ಮತ್ತು ಚಿಂತಾಮಣಿ	ಬೆಂಗಳೂರು ನಗರದ ಸಂಸ್ಕರಿಸಿದ ತ್ಯಾಜ್ಯ ನೀರನ್ನು ಕೋಲಾರ ಜಿಲ್ಲೆಯ ಹಾಗೂ ಚಿಕ್ಕಬಳ್ಳಾಪುರ ಜಿಲ್ಲೆಯ ಚಿಂತಾಮಣಿ ತಾಲ್ಲೂಕಿನ ಒಟ್ಟು 126 ಕೆರೆಗಳಿಗೆ ತುಂಬಿಸುವ ಏತ ನೀರಾವರಿ ಯೋಜನೆ ದ್ವಿತೀಯ ಹಂತದಲ್ಲಿ ಕೋಲಾರ ಹಾಗೂ ಚಿಕ್ಕಬಳ್ಳಾಪುರ ಜಿಲ್ಲೆಯ ಚಿಂತಾಮಣಿ ತಾಲ್ಲೂಕಿನ 257 ಕೆರೆಗಳಿಗೆ ನೀರು ತುಂಬಿಸುವ ಕಾಮಗಾರಿ.	45,500.00	14948.03	ಕಾಮಗಾರಿ ಪ್ರಗತಿಯಲ್ಲಿರುತ್ತದೆ.
5	ಬೆಂಗಳೂರು ನಗರ ಬೆಂಗಳೂರು ಗ್ರಾಮಾಂತರ ಚಿಕ್ಕಬಳ್ಳಾಪುರ	ಯಲಹಂಕ ದೇವನಹಳ್ಳಿ ಚಿಕ್ಕಬಳ್ಳಾಪುರ ಶಿಡ್ಲಘಟ್ಟ ಗೌರಿಬಿದನೂರು	ಬೆಂಗಳೂರು ನಗರದ ಹೆಬ್ಬಾಳ ನಾಗವಾರ ವ್ಯಾಲಿಯಿಂದ ತ್ಯಾಜ್ಯ ನೀರನ್ನು ಬೆಂಗಳೂರು ನಗರ, ಬೆಂಗಳೂರು ಗ್ರಾಮಾಂತರ ಹಾಗೂ ಚಿಕ್ಕಬಳ್ಳಾಪುರ ಜಿಲ್ಲೆಯ 65 ಕೆರೆಗಳಿಗೆ ನೀರು ತುಂಬಿಸುವ ಏತ ನೀರಾವರಿ ಯೋಜನೆ	84355.00	88679.00	ಕಾಮಗಾರಿ ಪೂರ್ಣಗೊಂಡಿದ್ದು ನಿರ್ವಹಣೆ ಕಾಮಗಾರಿ ಪ್ರಗತಿಯಲ್ಲಿರುತ್ತದೆ.

ಕ್ರ ಸಂ.	ಜಿಲ್ಲೆ	ತಾಲ್ಲೂಕು	ಕಾಮಗಾರಿಯ ಹೆಸರು	ಅಂದಾಜು ಮೊತ್ತ	ವೆಚ್ಚ	ಷರಾ
1	2	3	4	5	6	7
6	ಚಿಕ್ಕಬಳ್ಳಾಪುರ	ಬಾಗೇಪಲ್ಲಿ	ಬೆಂಗಳೂರು ನಗರದ ಹೆಬ್ಬಾಳ ನಾಗವಾರ ವ್ಯಾಲಿಯಿಂದ ತ್ಯಾಜ್ಯ ನೀರನ್ನು ಬೆಂಗಳೂರು ನಗರ, ಬೆಂಗಳೂರು ಗ್ರಾಮಾಂತರ ಹಾಗೂ ಚಿಕ್ಕಬಳ್ಳಾಪುರ ಜಿಲ್ಲೆಯ ಕೆರೆಗಳಿಗೆ ನೀರು ತುಂಬಿಸುವ ಏತ ನೀರಾವರಿ ಯೋಜನೆಯಿಂದ ಚಿಕ್ಕಬಳ್ಳಾಪುರ ಜಿಲ್ಲೆಯ ಬಾಗೇಪಲ್ಲಿ ತಾಲೂಕಿನ 24 ಕೆರೆಗಳಿಗೆ ನೀರು ತಿಮಬಿಸುವ ಎತ ನೀರಾವರಿ ಯೋಜನೆ	7000.00	3401.00	ಕಾಮಗಾರಿಯು ಪ್ರಗತಿಯಲ್ಲಿರುತ್ತದೆ.
7	ಬೆಂಗಳೂರು ನಗರ	ಯಶವಂತಪುರ	ಬೆಂಗಳೂರು ನಗರದ ವೃಷಭಾವತಿ ವ್ಯಾಲಿಯಿಂದ ದ್ವಿತೀಯ ಹಂತದಲ್ಲಿ ಸಂಸ್ಕರಿಸಿದ 243 ಎಂ.ಎಲ್.ಡಿ. ನೀರನ್ನು ಬೆಂಗಳೂರು ನಗರ, ಬೆಂಗಳೂರು ಗ್ರಾಮಾಂತರ, ತುಮಕೂರು ಜಿಲ್ಲೆಯ 70 ಕೆರೆಗಳಿಗೆ ನೀರು ತುಂಬಿಸುವ ಯೋಜನೆ .	108100.00	17000.00	ಕಾಮಗಾರಿಯು ಪ್ರಗತಿಯಲ್ಲಿರುತ್ತದೆ.
		ಯಲಹಂಕ				
	ಬೆಂಗಳೂರು ಗ್ರಾಮಾಂತರ	ನೆಲಮಂಗಲ				
	ತುಮಕೂರು	ತುಮಕೂರು ಗ್ರಾಮಾಂತರ				

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Socio-economic impact assessment of large-scale recycling of treated municipal wastewater for indirect groundwater recharge

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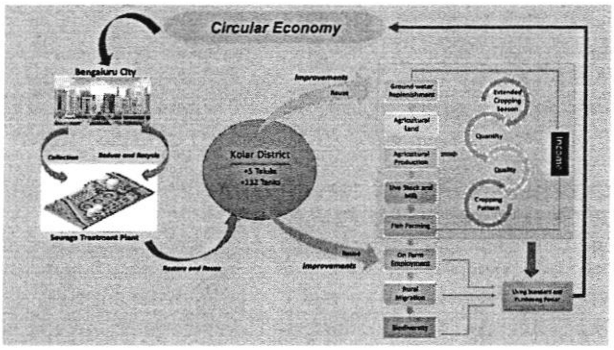
HIGHLIGHTS

- Large-scale recycling of treated wastewater for indirect groundwater recharge.
- Significant impact in the agricultural sector and socio-economic status.
- Enhancement in livestock, milk production, women's employment, and income.
- Contributed to the transition towards the circular economy in water sector.
- Need of the hour: Encouraging planning and management of wastewater reuse.

GRAPHICAL ABSTRACT



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ABSTRACT

Reusing treated wastewater is an emerging solution to address freshwater scarcity, and surface water contamination faced worldwide. A unique large-scale wastewater recycling project was implemented to replenish groundwater by filling secondary treated wastewater (STW) into existing irrigation tanks in severely drought-hit areas of the Kolar districts of Southern India. This study quantifies the socio-economic impacts of this large-scale indirect groundwater recharge scheme. The changes in areas receiving STW i.e., impacted areas and those areas which did not receive STW i.e., non-impacted areas was studied. Also, pre and post recycling changes were quantified in the Kolar district. The results show that surface water quality meets India's most stringent treated wastewater discharge standards prescribed by the Hon'ble National Green Tribunal. Due to these recycling efforts, significant improvements in groundwater level and quality were found. It was observed that there was a noticeable difference in agricultural cropping areas, seasons, patterns, and production between impacted and non-impacted areas. Post-recycling, farmers tended to cultivate cash and water-intensive crops over less water-intensive crops. During the post-recycling period, livestock and milk production also increased, and in impacted areas, it was significantly higher. Post-recycling, fish production increased and land prices per hectare increased by 118 % in impacted areas. The farmer's net income under flowers and vegetable farming increased by 202 % and 150 % respectively in impacted areas compared to non-impacted

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Abbreviations: APHA, American Public Health Association; ARB, Antibiotic Resistance Bacteria; BOD, Biological oxygen demand; CGWB, Central ground water board; COD, Chemical oxygen demand; DEIAA, District Level Environment Impact Assessment Authority; DO, Dissolved oxygen; EC, Electric conductivity; ESRI, Environmental Systems Research Institute; GoK, Government of Karnataka; GW, Groundwater; ICPMS, Inductively coupled plasma-mass-spectrometry; IS, Indian Standard; K&C, Koramangala and Challaghatta; LCMS, Liquid chromatography–mass spectrometry; MI & GW, Minor Irrigation and Groundwater; MIC, Minimum inhibitory concentrations; PCPP, Pharmaceutical and personal care products; PPP, Public-private partnership; SAR, Sodium absorption rate; STP, Sewage treatment plant; STW, Secondary treated wastewater; TN, Total nitrogen; TSS, Total Suspended Solids.

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areas. Furthermore, this project contributes to a circular economy transition in the water sector, which has economic, environmental, social, and cultural benefits. A key recommendation from the outcomes of the study is to draft and implement a policy that encourages the reuse of recycled water for groundwater recharge which in turn will improve the agro-economic system and food security.

1. Introduction

The world is facing challenges to manage severe water crises because of various factors such as population growth, rapid urbanization, rural electrification, industrialization, climate change, and irresponsible use of natural resources (Okello et al., 2015; Shan et al., 2020). This has prompted the policymakers to consider treated wastewater as a sustainable source of water supply (Okello et al., 2015; Shan et al., 2020). India is the largest extractor of groundwater (GW) in the world, and GW is primarily used for agricultural needs, followed by domestic and industrial consumption (World Bank, 2012; Suhag, 2016). India extracts more GW than China and the United States combined (World Bank, 2010; Chindarkar and Grafton, 2019). India does not only suffer from GW scarcity, but contamination of ground and surface water has also become a matter of high concern (Biswas and Hartley, 2017; Dangar et al., 2021).

The declining level of India's GW gained the attention of multiple stakeholders including policymakers, scientists, academia, national and international institutions (Bera et al., 2022). This has initiated exploring innovative, sustainable, affordable, and safe solutions for water management that contribute to improve the GW table (Bera et al., 2022). The development and expansion of wastewater treatment and reuse have the high potential to sustainably develop water ecosystems, improve socio-economic status, positively contribute to the food-water-energy cycle, and build a circular economy (Jhansi and Mishra, 2013; Sathaiah and Chandrasekaran, 2020; Kesari et al., 2021). In various countries, treated wastewater is considered an efficient and safe additional water resource and is used to mitigate water scarcity through recharging GW table. For instance, Israel (Icekson-Tal et al., 2003), Egypt (Aly Gondia et al., 2021), Kuwait (Aleisa, 2019), Spain (Jodar-Abellan et al., 2019), and Mexico (Mazari-Hiriart et al., 2008) have pioneered the technology to treat >90 % of wastewater and reuse it mainly for agricultural irrigation. Jordan (WHO, 2006), Singapore (Tortajada and Bindal, 2020), and Australia (ARMCAN et al., 2000) have set the standard/ guidelines to reuse treated wastewater for indirect and direct GW recharge. In Singapore recycled wastewater now meets 40 % of Singapore's water demand (Kog, 2020) whereas in Australia GW recharge initiative is fulfilling 4 % of the country's integrated water supply scheme to increase the security of urban water (Dillon and Arshad, 2016). Table 1 represents the status of these treated wastewater reuse efforts.

The practice of using untreated or partially treated wastewater for agricultural irrigation has also been historically prevalent in India (Minhas et al., 2022). But India has not taken any large-scale initiative to reuse treated wastewater for different purposes and indirect GW recharge. The National Environmental Engineering Research Institute (NEERI) in Nagpur, India conducted a pilot study to reuse treated municipal wastewater for indirect GW recharge by implementing the soil aquifer treatment (SAT) method (NEERI, 2015). The SAT refers to the artificial recharge or infiltration of wastewater through the vadose (unsaturated) zone to recharge the underlying aquifers (Essandoh et al., 2011). Few other studies with the same objective and methods were carried out in Ahmedabad and Chennai to assess the potential of SAT. However, there are no reports that reveal full-fledged implementation from anywhere in India (Deepa and Krishnaveni, 2012; Packialakshmi et al., 2015). Recently, the National Geophysical Research Institute of India implemented a program for indirect GW recharge through managed aquifer recharge. Percolation tanks were built through community participation to store rainwater (Nandan et al., 2021).

A review of these works reveals major gaps in the quantification of the socio-economic benefits of wastewater recycling projects which is the objective of this study. Large-scale recycling of secondary treated municipal wastewater (STW) was initiated in March 2018, in the Southern Indian city of Bengaluru, which currently generates about 1480 million litres per day (MLD) of STW. Under a project titled "Koramangala-Challaghatta Valley (K&C) project", nearly 440 MLD of STW from Bengaluru is being used for

Table 1
Treated wastewater reuse in different countries.

Country	Project name	% of Domestic wastewater treated and reused	Treatment method	Purpose/benefit
Israel (Kanarek and Michail, 1996; Icekson-Tal et al., 2003)	The Dan Region Reclamation Project	90 % Reuse- 69 %	Secondary, biological, and tertiary: soil aquifer treatment	60 %: Agricultural irrigation;10 %: environmental firefighting; increasing river flow; groundwater recharge.
Mexico (World Bank, 2018)	Atotonilco wastewater treatment project	60 % Reuse-46 %	Primary, secondary and biological	Agriculture irrigation (>90,000 ha land); urban landscaping. park development, domestic use, groundwater recharge.
Egypt (Aly Gondia et al., 2021)	Part of Sinai Peninsula Development Program	60 % Reuse-44 %	Primary, secondary and disinfection	Agricultural; horticulture; forest irrigation; urban landscaping; reduce pollutants discharged into the Nile River. Treated sludge (biosolids) used as fertilizer
Singapore (Djamel et al., 2019; Tortajada and Bindal, 2020)	Changi Water Reclamation project is one of the largest and most advanced reclamation facilities in the world (NEWater).	80 % Reuse-54 %	A four-stage treatment process: conventional, micro-filtration, reverse osmosis, and UV treatment	Industrial purposes; domestic uses; irrigation; recharge local aquifers; drinking water supplies to 5.7 million people.
Kuwait (Abusam and Shahalam, 2013; Aleisa, 2019)	–	75 % Reuse-58 %	Ultrafiltration through reverse osmosis tertiary treatment: sand filtration and chlorination	Agricultural irrigation (19 %); golf courses; community gardens; airports; governmental headquarters; landscapes on major highways and the new campus of Kuwait university.

indirect GW recharge in severe drought-hit neighbouring areas of Bengaluru, i.e., Kolar districts. Kolar, a neighbouring district of Bengaluru, had turned dry due to minimal or no rain for the last 10 years (CGWB, 2016). The GW resources in the Kolar district were categorized as "over-exploited" and this resulted in the depletion of the GW table in the district (DEIAA, 2020). The DEIAA, 2020 report indicates that the GW table in the affected area was ∼350–450 m from ground level. The persistent drought condition due to minimal rainfall and GW deficiency adversely impacted land use & irrigating areas, cropping pattern & productivity, socio-economic status, and migration of people to Bengaluru in search of employment (Ballukraya, 1997; Ramaiah et al., 2017; Garg et al., 2020). The focus of this study is to quantify the socio-economic impact of large-scale recycling of STW for indirect GW recharge. Specifically, the objectives were i) to determine the impact of indirect groundwater recharge on surface water quality, GW level, and GW quality, and ii) to determine the impact on socio-economic development and sustainability.

The socio-economic impact was quantified by comparing the socio-economic changes in the impacted locations (i.e., regions influenced by STW) with that of the non-impacted locations (i.e., regions not influenced by STW) of Kolar and a comparative study was also carried out between pre and post recycling period of the impacted areas.

2. Material and methods

2.1. Study area and the K&C valley project

Kolar district is in a semi-arid, drought-prone region located in the southeast of Karnataka state and covers an area of 3990 km^2 with a population of 1.54 million. The major source of livelihood in the district is agriculture and associated activities (Kolar district profile, 2009; Nagaraj et al., 2003). Agriculture is mostly dependent on rainwater, minor irrigation tanks, and borewells. Kolar district anciently had around 3000 man-made surface reservoirs/tanks which were the highest in Karnataka (GoK (Government of Karnataka), 2016). The tank water was used for various purposes, such as controlled irrigation, domestic and livestock needs, and also provided GW recharge (Lars Engberg-Pedersen, 2011). With little or no rains over the last 10 years, numerous tanks and borewells had gone dry and the GW table declined at alarming levels due to over-exploitation (CGWB, 2016). The depth of irrigation borehole wells had reached ∼250–300 m from the surface (Garg et al., 2020).

The K&C valley project is a large-scale (∼440 MLD), indirect GW recharge project initiated in March 2018, by the Minor Irrigation and Groundwater Development (MI&GW) Department of the Government of Karnataka to provide relief to these persistent drought-hit areas in the Kolar districts. The project aims to fill existing tanks using STW coming from the two sets of STPs located in Bengaluru. This project covers five Taluks (sub-unit of a District) in Kolar district namely Kolar, Srinivasapura, Mulabagilu, Bangarapet, and Malur. As of July 2022, a total of 137 tanks have been filled. The distribution of STW to existing tanks is divided into 12 clusters in order to track the supply, maintenance, and impact. A key map of the project is provided in **Fig. A.1** in appendix A. The project is designed/implemented by ensuring safety and awareness among the public, for ex: a bi-lingual (Kannada & English) board is placed near each tank that reads- "This water is meant for indirect groundwater recharge only". This project was designed to provide irrigation water to ∼24,000 ha of land, enhance water security for Kolar, re-establish plant and animal biodiversity, revive the rural economy, and ultimately improve the quality of life.

2.2. Data collection

2.2.1. Water quality analysis of secondary treated water and surface tank

The STW samples from STP and water samples from surface tanks receiving STW were collected and analysed following the standard methods (APHA, 2005). The test results were compared with the most stringent surface water discharge standards as prescribed by India's The Hon'ble National Green Tribunal (NGT) (shown in Table 3), which focuses on the discharge of treated wastewater into water bodies as well as for land disposal/applications (NGT, 2019). All the eight water quality parameters as per the Hon'ble NGT standard namely pH, biological oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), and ammonical nitrogen (NH_4-N), phosphate phosphorus (PO_4-P) and faecal coliform were monitored. In addition to the above eight parameters, the STW and surface water quality were also compared with the Central Polution Control Board (CPCB, 2013) standards for dissolved oxygen (DO), electric conductivity (EC), sodium absorption ratio (SAR), and Boron (B) (Table 3). All the water samples were tested in triplicates and average values along with standard deviation are presented as avg. ± std. dev. A detailed analysis for heavy metals was also carried out for the raw sewage entering STPs and STW using ICPMS (Quadrupole ICPM- Thermo X series II). An attempt was also made out to analyse pharmaceutical and personal care products (PCPPs) in the STW using LCMS (Dionex Ultimate 3000 (Thermo), micro-LC equipped with C18, 150 × 4.6 mm, 5 μm reversed phase column. Preliminary determination on antibiotic resistance bacteria (ARBs) was carried out using Ezy MIC™ Strips (HiMedia).

The STW reaching all 137 surface tanks of all 12 clusters are being monitored by the authors. The fourth tank in Cluster 2 i.e., Chowdenahalli Tank which was one of the earliest tanks to receive STW and is likely to be stabilized over this period was chosen as a representative tank for comparative analysis. However, one representative tank from each of the 12 clusters is reported in **Table B.1** of appendix B.

2.2.2. Groundwater (GW) level and quality

To find the impact of STW recycling on GW recharge and water quality, Narasapura borewell which was within 2 km of Chowdenhalli tank was identified for this study. Historical data on GW levels and water quality were obtained from the Karnataka Ground Water Authority (KGWA) and precipitation data were obtained from the Karnataka State Natural Disaster Monitoring Centre (KSNDMC). The parameters studied for GW quality analysis were pH, EC, total dissolved solids (TDS), nitrate (NO_3^-), sulfate (SO_4^{2-}), phosphate (PO_4-P), sodium (Na^+), Calcium (Ca^+), chloride (Cl^-), magnesium (Mg^+), potassium (K^+), and fluoride (F^+). Though one representative borewell data is provided in the main text, GW quality data of 12 representative borewells, around tanks (**Table B.1**), for all 12 clusters is provided in **Table B.2** of appendix B.

2.2.3. Socio-economic status

Villages that are nearest (within 2–3 km) to the tanks filled with STW have been considered "impacted" or experiencing benefits from STW recycling and villages where the tank has not received STW continue to remain status quo of being drought-prone/rain-fed, are considered "non-impacted".

To assess the socio-economic impact of the K&C valley project, a two-step data collection process was followed i.e., 1) approaching farmers through a structured household survey and 2) reaching out to different government organizations of Kolar district such as the department of agricultural & horticulture, department of veterinary sciences, Kolar-district co-operative milk producer's societies union ltd., department of fishery sciences and district surveillance office. Consecutive data for a 6-year period, between 2016 and 2021, were collected for Kolar district from these organizations. Data between 2016 and 2018 were categorized as 'pre-recycling' and that between 2019 and 2021 as 'post-recycling' data.

The present study covered 12 villages in the Kolar district comprising 6 villages from impacted areas and 6 from non-impacted areas to carry out a comparative study to analyse the impact of the K&C valley project and its sustainability. It was ensured that the selected impacted and non-impacted villages were within the Kolar district with the same geographical, hydrological, socio-cultural, agro-climatic, and environmental conditions. The largest distance between impacted and non-impacted areas was just 55 km. Also, the impacted and non-impacted groups of farmers represent typically the predominant 'small and marginal farmers' (SMF, 1-2 ha land holding) and have been carrying out a similar pattern of agricultural

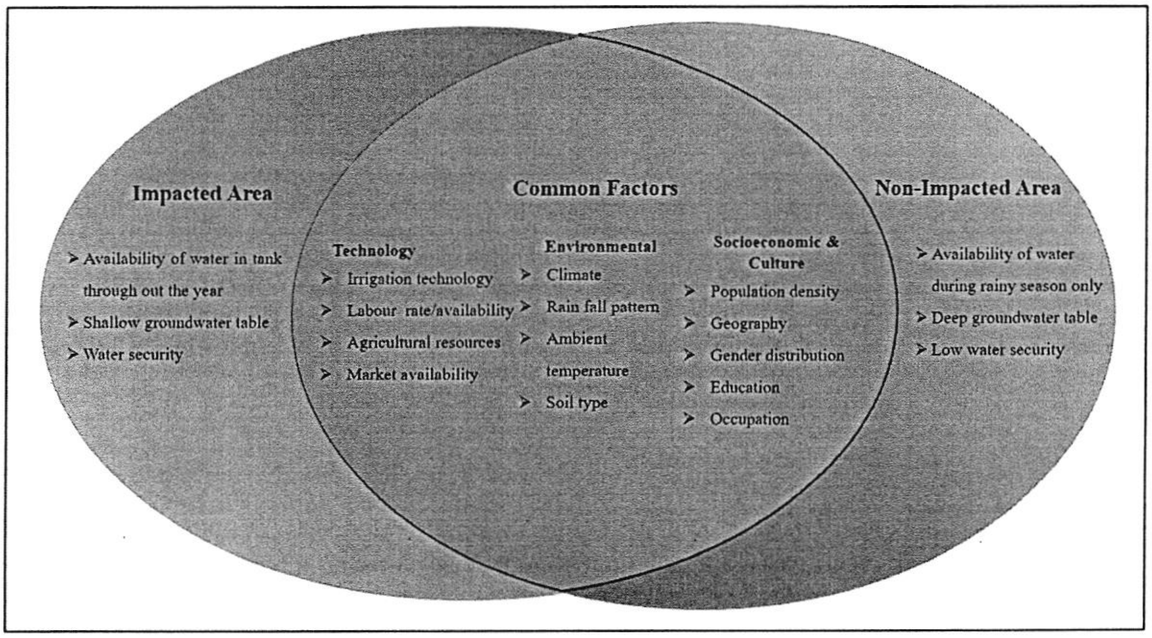

Fig. 1. A schematic framework indicating common and differentiating factors.

activities for a reasonably long period. The predominant difference between the impacted and non-impacted areas was the availability of STW in the tanks and shallow GW levels because of this recycling. A schematic framework indicating the common and the differentiating factors between impacted and non-impacted areas is provided in Fig. 1.

Data for the year 2021 was collected from impacted and non-impacted study areas. The number of farmers selected was based on the probability proportional to the size of SMF of the 12 villages. The sample size (n) of farmer's household units in the study area was determined by applying the following formula (Arkin and Colton, 1950; Kadam and Bhalerao, 2010; https://www.surveymonkey.com/mp/sample-size-calculator/) at 95 % of confidence level, where: z = z-score (1.96), d = margin of error (0.05), p = estimated population proportion (0.5, this maximizes the sample size) and N = total number of farmer's household (1035).

$$\frac{Nz^2p(1-p)}{Nd^2+z^2p(1-p)}$$

According to this formula, 280 sample sizes were found to be ideal for the random sampling method, hence a total of 280 farmers were selected for the present study. The sample distribution of impacted and non-impacted areas is presented in Table 2 and a schematic diagram of the methodology has been represented in Fig. 2.

Table 2
Selection of sample farmer.

Impacted area			Non-impacted area		
Name of village	Number of farmer's household	Sample farmers	Name of village	Number of farmer's household	Sample farmers
Narsapur	130	35	Baiyappanahalli	105	30
Chowdenahalli	100	30	Imarakunte	70	25
Doddvallabbi	80	15	Marasanapalli	85	25
Dinnehosahalli	85	20	Rayalapad	70	20
Kavaraganahalli	90	25	Chillarapalli	60	15
Doddaleri	70	15	Beemaganapalli	90	25

2.2.4. Questionnaire

Field/household surveys have emerged as a standard tool for empirical research in social sciences (Vehovar and Lozar-Manfreda, 2008). In order to achieve the objective of the present study a questionnaire was designed that included 64 questions distributed over 4 segments as represented below. The data set chose a nearly homogenous type of farmers in this region and the critical differences between the two groups were only the access and availability of GW for agriculture and related livelihoods.

i) general information and socioeconomic status including name, age, education, occupation, and income of the respondents.
ii) agricultural activities including information about land ownership, agricultural land, crop pattern/diversification, crop production, source and method of irrigation, no. of livestock, milk production, labour utilization, and sources of income.
iii) lifestyle and property enhancement including the recent purchase of household amenities, agricultural assets, land, refurbishment of house, land value (pre- and post-recycling), and others.
iv) public, animal health, and perception-related questions include whether the incidence of diseases mainly waterborne (cholera, diarrhea, typhoid, etc.) has increased during post-recycled water use, the status of animal health/disease/mortality changes during post-recycling, a general opinion about the negative and positive impact of the project and suggestions.

The questionnaire was structured to be precise on "open and closed-ended questions", and multiple-choice questions to obtain specific data points. The household survey was conducted by administrating a questionnaire from March 2022–May 2022. Verbal informed consent was obtained from respondents before administering the questionnaire and the purpose of the study was conveyed (Lawton et al., 2017; Roy et al., 2018). Head of the families in the study areas were the primary respondents.

2.2.5. Data analysis

An independent student's t-test was performed to verify the statistical significance difference in obtained data between impacted and non-impacted areas. The results are represented as follows: (a) NS (not significant) for $p > 0.05$, (b) $^{*}p < 0.05$, (c) and $^{**}p < 0.01$. The percentage of change was carried out to analyse the differences between pre-and post-

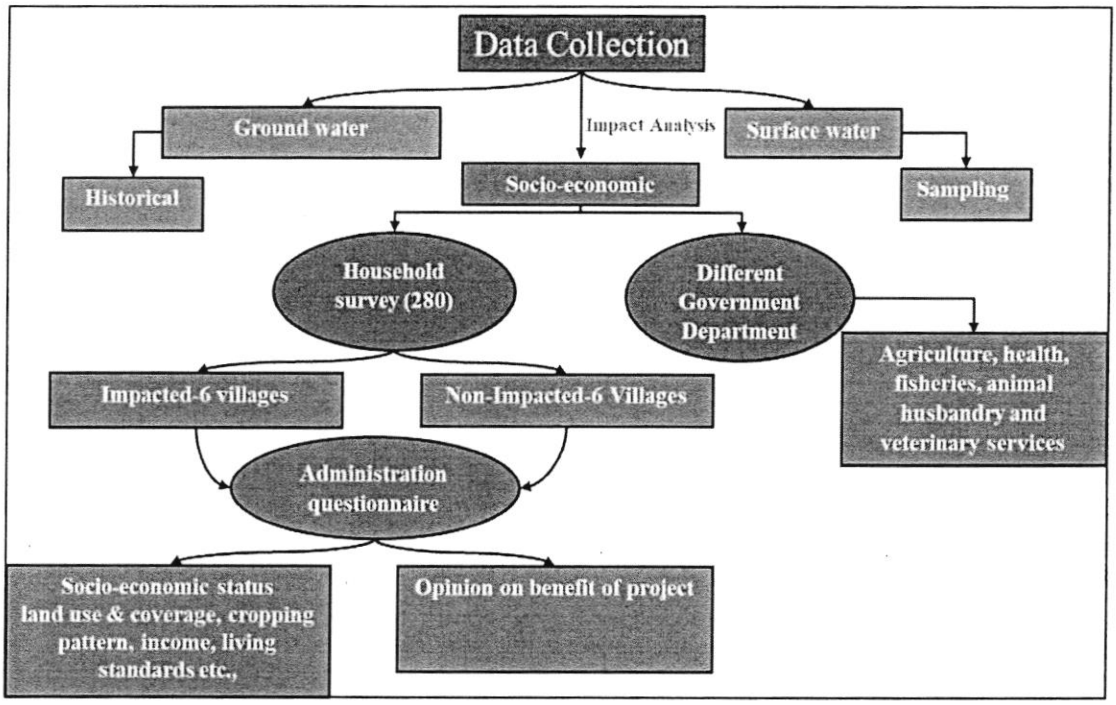

Fig. 2. Schematic diagram of the methodology.

recycling data of Kolar district by taking an average of 3 years for every group.

3. Results and discussion

3.1. Physio-chemical and microbiological analysis of secondary treated water and surface water

The result of the physio-chemical and microbiological analysis of STW at the outlet of STP and surface water of Chowdenahalli tank is presented in Table 3. It indicates that STW from STPs and Chowdenahalli tank were meeting the Hon'ble NGT standard (except for faecal coliform in STW) to dispose of the water into water bodies and for land disposal/applications (NGT, 2019). The results were also meeting three important criteria of the CPCB "Designated best uses of water" i.e., bathing water quality (B), propagation of wildlife and fisheries (D), and irrigation (E).

Table 3
Water quality of secondary treated water and surface tank.

Parameters	[1]Hon'ble NGT standard	[2]CPCB (Designated-best-use water quality)	STW from the outlet of STP	Chowdenahalli tank
pH	6.5–9.0	6.5–8.5 $^{A-E}$	7.6	7.4
BOD_5 (@20 °C) (mg/l)	10	$\leq 2^A$, $\leq 3^B$	9 ± 1.0	3.7 ± 0.8
COD (mg/l)	50	NS	48 ± 4.0	45 ± 4.0
TSS (mg/l)	10	NS	8 ± 2.2	6.5 ± 1.5
TN (mg/l)	10	NS	7.8 ± 2.5	1.5 ± 0.1
NH_4 -N (mg/l)	5	1.2^D	4.6 ± 0.8	0.1 ± 0.02
Faecal Coliforms (MPN/100 ml)	< 230	$\leq 50^A$, $\leq 500^B$ $\leq 5000^C$	280 ± 20	190 ± 26
PO_4- P (mg/l)	1	NS	0.8 ± 0.3	0.3 ± 0.08
DO (mg/l)	NS	$\geq 6^A$, $\geq 5^B$, $\geq 4^{C, D}$	4.5	8.5 ± 2.1
EC (@25 °C, μs/cm)	NS	2250	707	587 ± 21.5
SAR (mEq/l)	NS	26^E	9.3	3.1 ± 1.0
B (mg/l)	NS	2^E	1.2 ± 0.4	0.5 ± 0.18

Source: [1]NGT, 2019; CPCB, 2013 cpcb.nic.in.

Note: A: Drinking Water Source without conventional treatment but after disinfection; B-Outdoor Bathing; C: Drinking water source after conventional treatment and disinfection; D-Propagation of Wildlife and Fisheries; E-Irrigation, Industrial Cooling, Controlled Waste disposal.

NS: not specified; SAR-sodium absorption ratio; DO- dissolved oxygen.

3.2. Analysis of heavy metals, personal care, and pharmaceutical products (PCPPs)

Given the risks of heavy metals on human health, heavy metal is being monitored regularly, not only in the STW generated in STPs but also in raw sewage entering STPs. Table 4 gives a typical analysis of the heavy metals in the raw sewage entering the STPs and STW being supplied from the STPs to the tanks. As can be seen from Table 4, both the raw sewage and STW meet the existing drinking water standards IS 10500 for heavy metals (Rao et al., 2021). The STW has been constantly monitored for heavy metal content and has been reported to be within acceptable limits (Singh, 2020).

It is important to note that, based on the analysis of heavy metals in raw sewage and STW at the STPs, it is clear that there are no serious threats to human health as far as heavy metals are concerned. Further, the sewage generated undergoes a four-layered purification process namely 1. an anaerobic stage during its conveyance in the sewerage system, 2. a conventional aerobic sewage treatment system that meets the NGT standards (NGT, 2019) (Table 3), 3. a > 14 days residence time in contact with algal system in the open water body and 4. a long passage over hundreds of meters of soil contact before recharging GW. This greatly enhances the potential for nearly complete biodegradation of the slow-to-degrade PCPPs (Narain-Ford et al., 2020). Studies on PCPPs for these locations are underway and preliminary results indicate that common PCPPs such as Ibubrofen, Diclofenac, Azithromycin, Ciprofloxacin, Cetirizine, and Triclosan were absent in the STW.

3.3. Impact on groundwater level and quality

Fig. 3 represents the historical GW level of Narsapura borewell which was in the nearby vicinity (within 2 km) of impacted Chowdenahalli tank. It can be observed from Fig. 3 that the depth of the water level in the Narsapura borewell was approximately 18 mbgl in (Jan-May) 2019

Table 4
Summary of heavy metals analysis.

S.No.	Metals, metalloids, and heavy metals	IS 10500 (mg/l)	Raw sewage (mg/l)	Secondary treated wastewater(mg/l)
1	Iron (Fe)	3	0.40	0.36
2	Manganese (Mn)	2	0.16	0.02
3	Zinc (Zn)	5	0.02	BDL
4	Cadmium (Cd)	2	BDL	BDL
5	Lead (Pb)	0.1	BDL	BDL
6	Arsenic (As)	0.2	0.001	0.001
7	Chromium (Cr^{+5})	0.1	0.004	<0.1
8	Nickel (Ni)	3	0.02	0.028
9	Copper (Cu)	3	0.00005	0.00
10	Aluminium (Al)	0.2	0.03	BDL
11	Barium (Ba)	0.7	0.01	0.045
12	Boron (B)	0.5	0.04	0.021
13	Selenium (Se)	0.01	0.008	BDL
14	Silver (Ag)	0.1	0.00041	BDL
15	Mercury (Hg)	0.001	0.004	BDL
16	Molybdenum (Mo)	0.07	0.003	0.001

Note: BDL is below the detection limit of 1×10^{-6} mg/l.

whereas it reached 3 mbgl in July 2019. A clear positive impact on GW levels (83 %) was observed in the studied borewell as an immediate impact of recycling STW. It can be confirmed that the surface water has infiltered into the subsurface and percolated vertically through soil permeability. The downward flow of water through gravity reaches the water table and increases the levels in the GW reservoir. Similar studies are also reported by Nandan et al. (2021) who have reported improved GW conditions in water-scarce regions through managed aquifers. Shawaqfah et al. (2021) reported GW table recovery to 39.68 m by using treated wastewater as GW recharge. Fig. 3 also represents the precipitation data which proves that 2018–2019 was a rain deficit year in the Kolar district but still the water level increased at the studied location which significantly confirms that the increase in GW level is a direct impact of STW recycling which is filled in the respective tank at the studied borewell location.

Table 5 represents a comparison between the pre-recycling (2018) and post-recycling (2021) phases in the historical water quality data of the Narsapura borewell. It can be observed from Table 5 that the GW quality has improved post recycling in the case of all the studied significant parameters. It can be observed that post recycling there was no major change in the pH and the nature of the GW was alkaline (pH = 7.5). Significant reduction was observed in NO_3^- (25 %), SO_4^{2-} (42 %), F^+ (52 %), PO_4-P (20 %), and Cl^- by (52 %) when compared with pre recycling phase. The concentration of cations was also reduced where a reduction in Ca^+ concentration was by 22 %, Na^+ by 13 %, Mg^+ by 36 %, and K^+ by 56 %. It can be concluded that the water quality parameters improved due to the movement of water from the surface tank and through infiltration into the soil, where the water percolates downward deep in the soil and further reaches the water table, and also due to the dilution factor. Analyzing the GW quality is important as it determines its suitability for reuse in irrigation. Bekele et al. (2011) have reported reductions in phosphorous by 30 %, 66 % for fluoride, and 51 % for organic carbon due to GW recharge experimental studies in managed aquifer systems. The results of the presented study are also supported by the outcomes of Asano and Cotruvo (2004), Bekele et al. (2013), Packialakshmi et al. (2015), and Shawaqfah et al. (2021).

3.4. *Impact on agricultural activities and socio-economic status*

This section represents the overall impacts of the K&C valley project in different socio-economic sectors such as:

3.4.1. *Impact on land use and land coverage (LULC)*

3.4.1.1. Comparison between pre- to post-recycling period. Fig. 4 indicates the topographical view of land use and land coverage in the Kolar district. Analysis of land use and land cover of any area is an important research aspect to understand environmental change and sustainability (Vivekananda et al., 2021). The analysis shows almost 6 times improvement in the water spread area of water bodies from 9.01km^2 in 2017 to 61km^2 in 2022. It was observed that area under trees increased from 124 km^2 to 177 km^2 and cropping land increased from 2477km^2 to 2584 km^2 during the same period. A major change was observed in the area under flooded vegetation indicating a 67 times improvement from 0.07 km^2 in 2017 to 4.8 km^2 in 2022. The data for fallow land and rangeland indicated a decrease of 41 % and 32 % during the same period. Fig. 4 establishes the contribution of filled water bodies and minor tanks in the improvement of areas of agricultural or productive land.

3.4.2. *Impact on agricultural land*

3.4.2.1. Comparison between impacted and non-impacted areas. Fig. 5(a) represents that the area under cultivation of vegetables for the year 2021 was relatively higher in impacted areas (57 ha) compared to non-impacted areas (29 ha). The computed student's *t*-test value confirms that there was

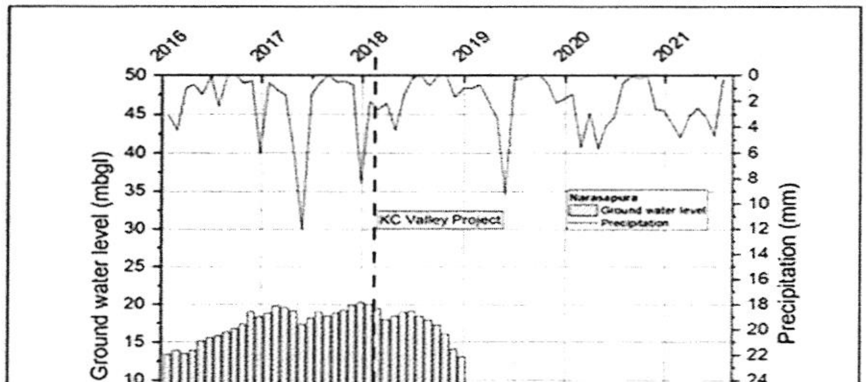

Fig. 3. Change in groundwater level (Narsapura borewell) between pre- to post-recycling period. Source: KGWA & KSNDMC.

Table 5
Change in groundwater quality between the pre- to post-recycling period.

Sl. No	Parameters (unit)	Pre-recycling	Post-recycling
1	pH	7.2	7.5
2	EC (μs/cm)	950 ± 68	404 ± 55
3	TDS (mg/l)	368 ± 22	108 ± 28
4	NO_3^- (mg/l)	2.4 ± 1	1.8 ± 0.4
5	SO_4^{2-} (mg/l)	21 ± 6.2	12 ± 1.8
6	PO_4-P (mg/l)	0.1 ± 0.03	0.08 ± 0.01
7	Na^+ (mg/l)	63.5 ± 12	55 ± 10
8	Cl^- (mg/l)	50.7 ± 8.2	24 ± 5
9	Ca^+ (mg/l)	46.2 ± 8.8	36 ± 8.2
10	Mg^+ (mg/l)	44.7 ± 16	28.2 ± 6.4
11	K^+ (mg/l)	16.2 ± 5.1	7 ± 2.2
12	F^+ (mg/l)	0.84 ± 0.8	0.4 ± 0.1

a significant difference in the mean value of the area under cultivation of vegetables ($p < 0.01$). The student's *t*-test value confirms that there was a significant difference in the mean value of the area under cultivation of cereals ($p < 0.05$), fruits ($p < 0.01$), and flowers ($p < 0.01$) between impacted and non-impacted areas. It was observed that the area under plantation and pulses was also high in impacted areas compared to non-impacted areas, but a significant difference was not found.

3.4.2.2. Comparison between pre- to post-recycling period.

Fig. 5(**b**) indicates a change in agricultural land of Kolar district from the pre- to post-recycling period. It was observed that the average area under cultivation of vegetables increased from ~20,000 ha to ~33,000 ha from the pre- to post-recycling period which indicates an increase of 65 %. During the same period average area under cultivation of flowers, fruits, and plantation and spices & aromatic (SP & Aroma) crops increased by 68 %, 50 %, 42 %, and 33 % respectively. A minimum increase of 10 %, 9 %, and 7 % was observed for areas under cultivation of pulses, cereals, and oil seeds respectively. It is obvious that due to the assured availability of water the cropping pattern was changed from low water requiring crops (e.g., pulses, oil seed) to high water requiring and water-intensive /water sensitive crops (vegetables, flowers, etc.).

3.4.3. Impact on agricultural (crop) production

3.4.3.1. Comparison between impacted and non-impacted areas.

Fig. 6(**a**) represents that the production of different plantation crops was relatively higher for the year 2021 in impacted areas (23 metric tons (MT)/ha) compared to non-impacted areas (15MT/ha). The computed student's *t*-test value indicates that there was a significant difference in the mean production of plantation crops ($p < 0.01$). Similarly, the yields of vegetables, flowers, and cereals were high in impacted areas. The student's *t*-test value confirms that there was a significant difference in the mean yield of vegetables ($p < 0.01$), flowers ($p < 0.01$), and cereals ($p < 0.05$) between impacted and non-impacted areas. It was also observed that the production of pulses was high in non-impacted areas compared to impacted areas, but a significant difference was not found.

3.4.3.2. Comparison between pre- to post-recycling period.

Fig. 6(**b**) indicates improvement in crop production from the pre-to-post recycling period where the average production of flowers, vegetables, plantation, fruits, spices, and aromatic plants and pulses increased by 80 %, 70 %, 36 %, 35 %, 28 %, and 12 %, respectively. While during the same period production of cereals and oil seeds increased by 11 % and 7 % only. It is visible that agricultural production has increased significantly as a result of the assured availability of irrigation water throughout the year, the revival of the GW table, and possibly due to improved GW quality (Theregowda et al., 2019; Tymchuk et al., 2020; Ofori et al., 2021; Partyka and Ronald, 2022). Secured water availability throughout the year resulted in an extended cropping season and a change in cropping pattern. Considering the multidimensional benefits of water security, farmers appear to be more inclined towards cash crops (vegetables, flowers) for quick returns and higher benefits.

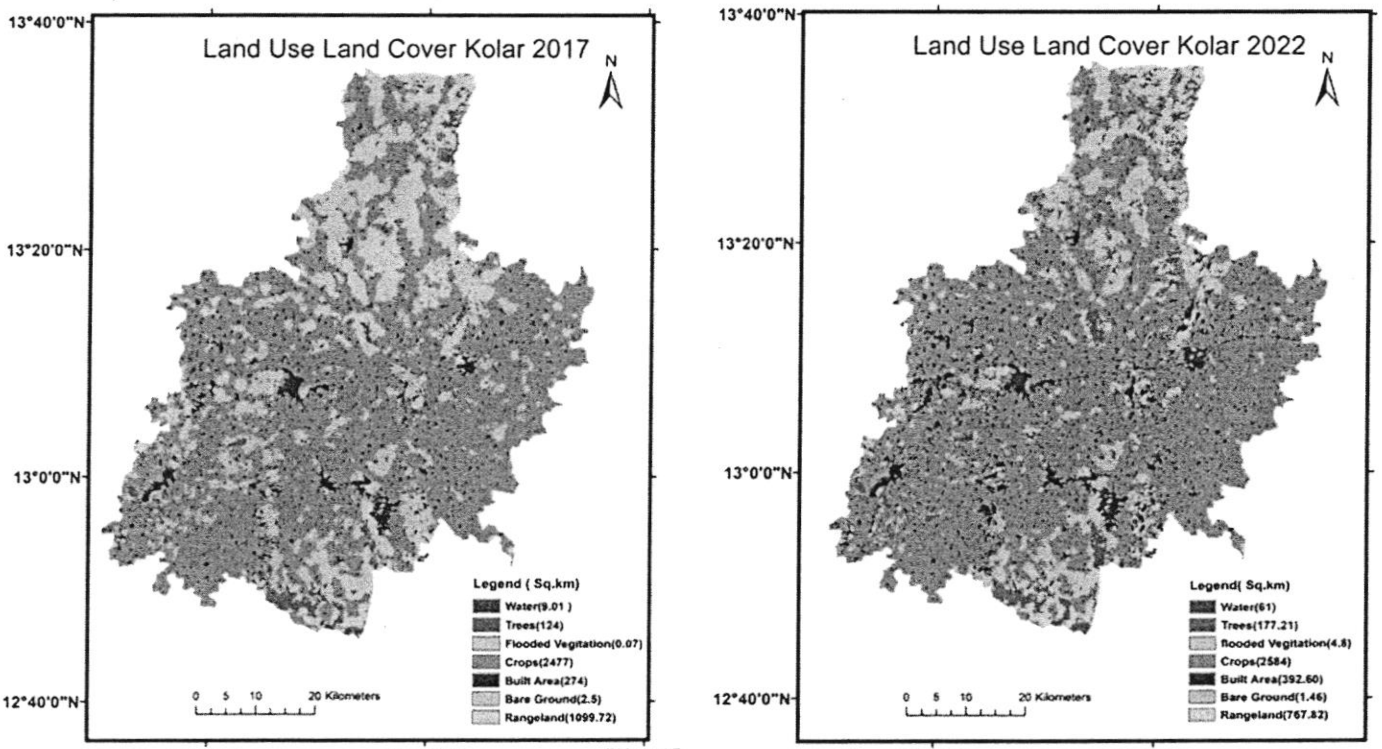

Fig. 4. Change in land use and land cover between 2017 and 2022 in the Kolar district. Source: Environmental Systems Research Institute (ESRI) land cover 2017 to 2022.

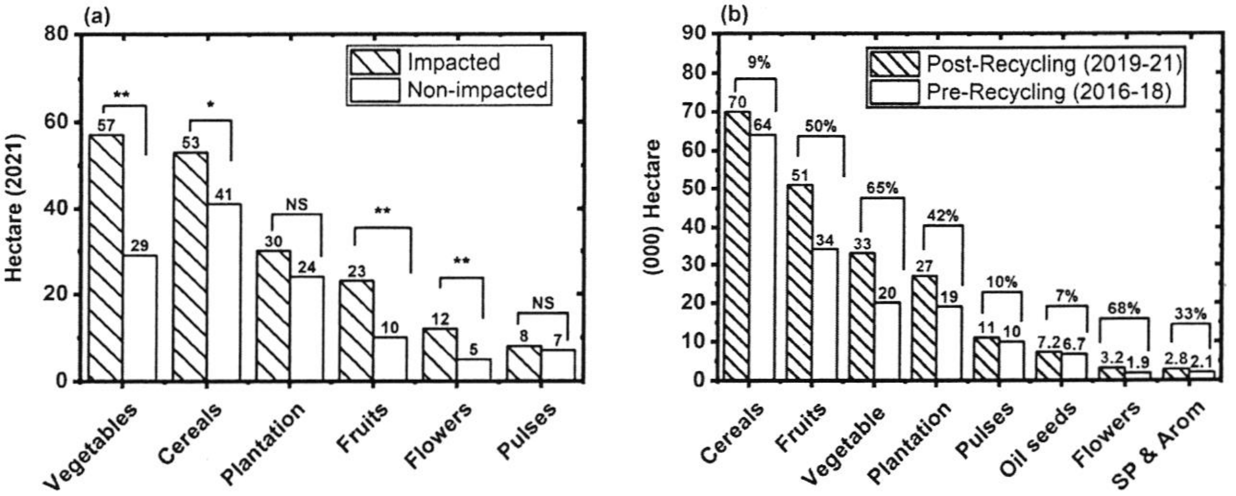

Fig. 5. Change in agricultural land (a) Comparison between impacted and non-impacted areas (b) Comparison between pre- to post-recycling period.
Source: (a) Household survey (b) Department of Agriculture & Horticulture, Kolar
Note: Student's *t*-test value: - vegetables (5.02), Cereals (2.61), Plantation (1.39), Fruits (3.93), Flowers (2.83), Pulses (0.39). NS- not significant for $p > 0.05$, $^{*}p < 0.05$, $^{**}p < 0.01$. Plantation- cashew, silver oak, eucalyptus, coconut, areca nut, tamarind, and mulberry; Vegetables- tomato, potato, beans, cabbage, green chili, capsicum, carrot, etc.; Fruits- mango, banana, sapota, guava, grapes, watermelon, pomegranates, papaya, etc.; Cereals- ragi, paddy, maize, jowar, minor millets, etc.; Flower- marigold, chrysanthemum, jasmine, rose, crossandra etc.; Pulses-red gram, field bean, toor, cowpea, horse gram, green gram, etc. Oil seed – ground nut, sunflower.

3.4.4. Impact on livestock rearing pattern and milk production

3.4.4.1. Comparison between impacted and non-impacted areas (livestock). Fig. 7 (a) indicates that the number of sheep, goats, cows, and buffalo was higher in impacted areas compared to non-impacted areas in 2021. The computed student's *t*-test value confirms that the difference was significant for sheep ($p < 0.5$), goat ($p < 0.5$), cow ($p < 0.01$), and buffalo ($p < 0.01$).

3.4.4.2. Comparison between impacted and non-impacted areas (milk production). The extent of milk production in impacted and non-impacted areas is presented in Fig. 7(b). The total milk production per day was significantly ($p < 0.01$) higher in impacted areas compared to non-impacted areas at 2141 and 1394 litre.

3.4.4.3. Comparison between pre- to post-recycling period (livestock). Fig. 7(c) shows that the average number of livestock was relatively increased during the post-recycling compared to the pre-recycling period, however, there was no change observed in the pattern of livestock rearing. The average number of cattle increased from 0.16 million to 0.22 million and buffalos also increased from 0.03 million to 0.04 million from the pre- to post-recycling period which indicates a growth of ~37 % and ~33 % respectively. Other livestock such as pigs, sheep, goats, and poultry also witnessed an increase from the pre-to-post recycling period with a reported growth of 100 %, 37 %, 33 %, and 27 % respectively.

3.4.4.4. Comparison between pre- to post-recycling period (milk production). Fig. 7(d) demonstrates taluk level pre- and post-recycling data for the average milk production. It indicates that the average milk production

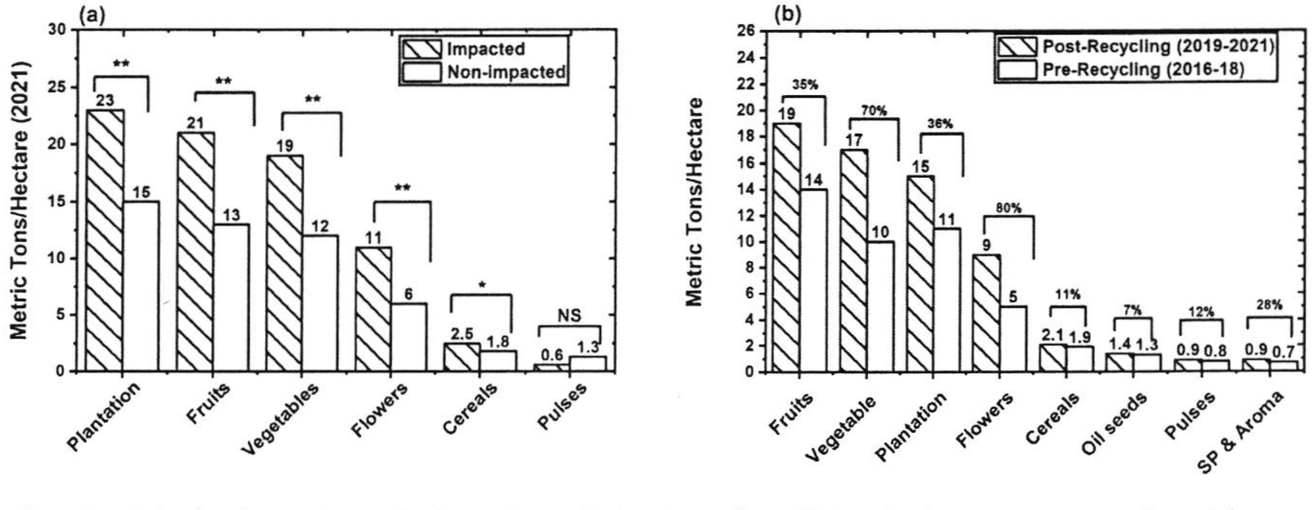

Fig. 6. Change in agricultural production; (a) Comparison between impacted and non-impacted areas (b) Comparison between pre- to post-recycling period.
Source: (a) Household survey (b) Department of Agriculture & Horticulture, Kolar
Note: Student's *t*-test value: - Plantation (4.08), Vegetables (4.67), Flowers (3.79), Cereals (2.91), Fruits (12.08), Pulses (1.89). NS- not significant for $p > 0.05$, $^{*}p < 0.05$, $^{**}p < 0.01$. Plantation- cashew, silver oak, eucalyptus, coconut, areca nut, tamarind, and mulberry; Vegetables- tomato, potato, beans, cabbage, green chili, capsicum, carrot, etc.; Fruits- mango, banana, sapota, guava, grapes, watermelon, pomegranates, papaya, etc.; Cereals- ragi, paddy, maize, jowar, minor millets, etc.; Flower- marigold, chrysanthemum, jasmine, rose, crossandra, etc.; Pulses-red gram, field bean, toor, cowpea, horse gram, green gram, etc. Oil seed – ground nut, sunflower.

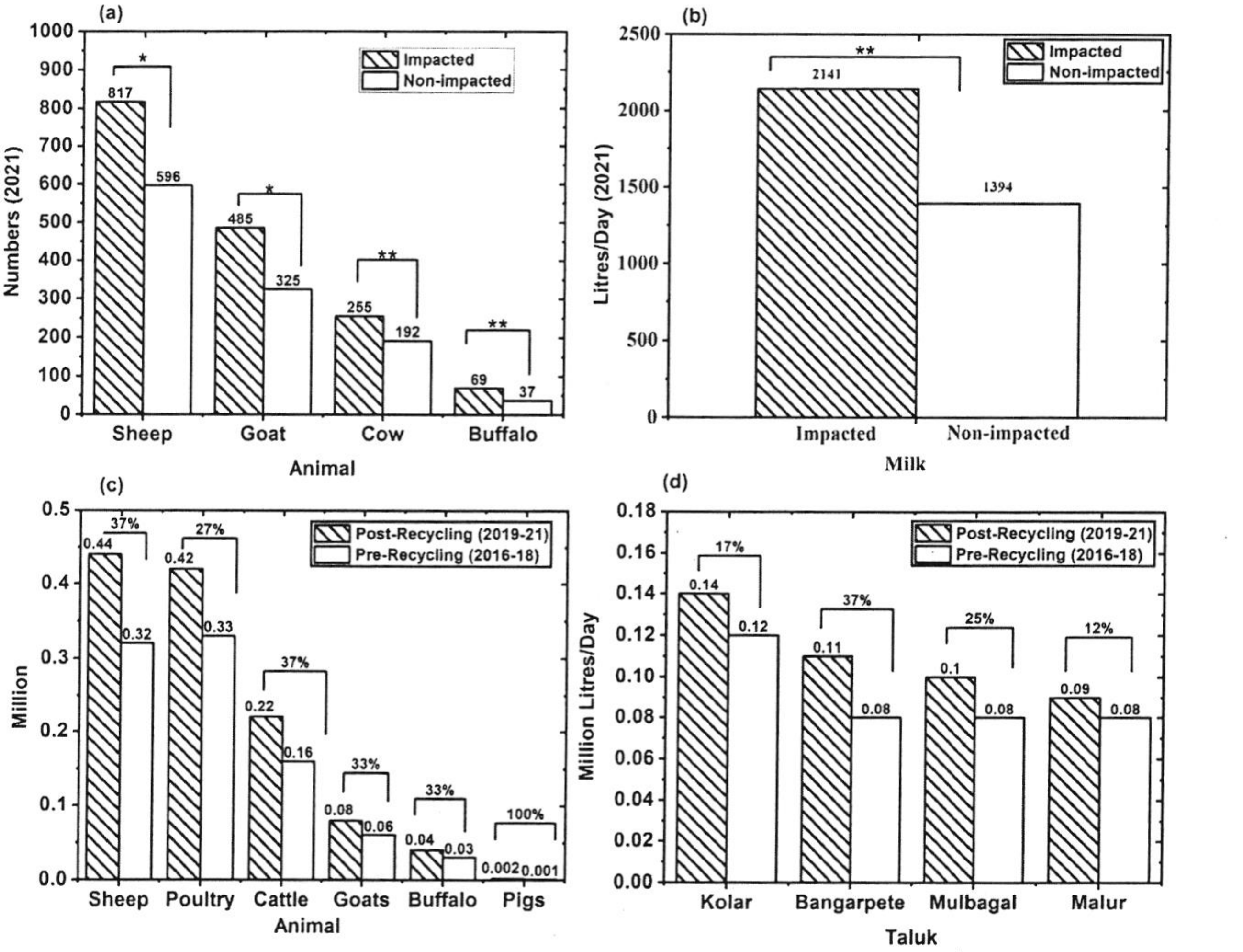

Fig. 7. Change in livestock pattern and milk production; (a) Comparision between impacted and non-impacted areas in pattern of livestock (b) milk production (c) Comparision between pre to post recycling period in the pattern of livestock (d) milk production.
Source: (a & b) Household survey; (c) Department of Veterinary Sciences, Kolar; (d) Kolar-Chikkaballapur District Co-operative Milk Producer's Societies union Ltd. Kolar.
Note: Student's *t*-test value: - (a) Sheep (20.05), Goat (2.19), Cow (3.77), Buffalo (3.18); (b) milk (7.14). significant for $p^* < 0.05$, $^{**}p < 0.01$.

increased during the post- recycling period compared to the pre-recycling period. Milk production was increased by 37 % from 0.08 MLD to 0.11 MLD at Bangarpete. Similarly, an increase of 25 %, 17 %, and 12 % in average milk production was reported at Mulbagal, Kolar, and Mular taluks, respectively. Farmers also revealed that the quality and quantity of milk have been improved due to the increased use of green fodder in the daily ration of animals. It is evident from the results that the availability of water has a positive impact on livestock rearing along with milk production.

3.4.5. *Impact on fish production*

3.4.5.1. Comparison between pre- to post-recycling period. Fig. 8(**a**) indicates a steep rise in fish farming during the post-recycling period in all taluks of the Kolar district. The highest increase of 300 % was observed at KGF followed by Bangarpete (221 %), Kolar (133 %), Mulbagal (49 %), and Malur (29 %) from the pre- to post-recycling period. Fish farming is one of the most important allied sectors in the Kolar district and occupies an important place in socio-economic development. There were 8091 fish farmers in the Kolar district who were involved in fisheries on a full-time basis and 94,946 fish farmers had taken up fisheries activity as a subsidiary occupation (Department of Fishery Sciences, Kolar, 2021).

3.4.5.2. Comparison between impacted and non-impacted areas. It could be observed from Fig. 8(**b**) that the average fish production increased by 133 % from 647MT to 1510MT from the pre- to post-recycling period in impacted areas whereas only an 8 % increase was reported from non-impacted areas. The improvement in fish production echoes various supporting statements which elaborated that treated wastewater is favourable for aquaculture due to the presence of a higher concentration of organic matter and other nutrients such as ammonia, nitrite, and potassium which is important for fish growth (Zaibel et al., 2019 & Zaibel and Zilberg, 2021).

3.4.6. *Impact on land values*

3.4.6.1. Comparison between impacted and non-impacted areas. Fig. 9 represents that the mean price of agricultural land was substantially higher (Rs.2.4 million/ha) in the impacted areas compared to the non-impacted areas (Rs.1 million/ha). From the pre- to post-recycling period land value in impacted areas observed a sharp escalation where prices increased by 118 % compared to a mere 25 % increase in non-impacted areas. Assured availability of water throughout the year resulted in fertile and productive land and has caused this change (Rondhi et al., 2018).

3.4.7. *Impact on labour utilization*

3.4.7.1. Comparison between impacted and non-impacted areas. It could be observed from Fig. 10(**a**) that the total number of men labour utilization for the year 2021 in crop activities, livestock, and the non-farm sector was higher in impacted areas at 4248, 2568, and 1149 compared to non-

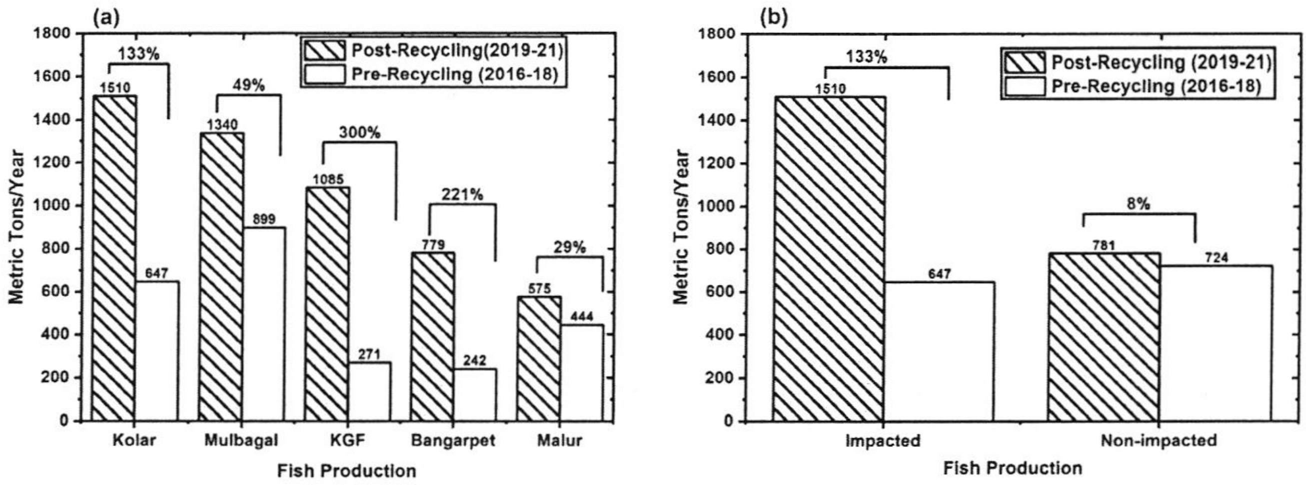

Fig. 8. Change in fish farming (a) Comparison between pre- to post-recycling period (b) Comparison between impacted and non-impacted areas.
Source: (a) & (b) Department of Fishery Sciences, Kolar.
Note: Impacted-Kolar taluk and Non-impacted: Srinivaspur taluk.

impacted areas with 3279, 2019 and 930 respectively. The computed student's *t*-test value indicates that there was a significant difference in the mean score of men's labour utilization in the crop activities ($p < 0.01$), and livestock sector ($p < 0.05$) between impacted and non-impacted areas. However, there were no significant differences observed in the mean score of men's labour utilization in non-farm activities.

Fig. 10(**b**) indicates that the total number of women labour utilization for the year 2021 in crop activities was higher in impacted areas (6563) compared to non-impacted (4155) areas. Similarly, during the same period, there were substantially higher women's labour utilization observed in impacted areas in livestock and the non-farming sector at 4463 and 2501 compared to non-impacted areas with 2895 and 1122 respectively. The computed student's *t*-test value indicates that there was a significant difference in the mean score of women's labour utilization in the crop activities ($p < 0.01$), livestock sector ($p < 0.01$), and non-farm activities ($p < 0.01$) between impacted and non-impacted areas.

An increase in women's employment pattern reveals that the revival of agricultural activities expanded women's employment opportunities thereby providing unique potential for women's empowerment and influencing involvement in decision making. This observation also supports various studies indicating that empowerment and financial contribution are the most important factor determining the involvement of women in decision-making (Lohani and Aburaida, 2017; Pandey et al., 2021; Kochar et al., 2022).

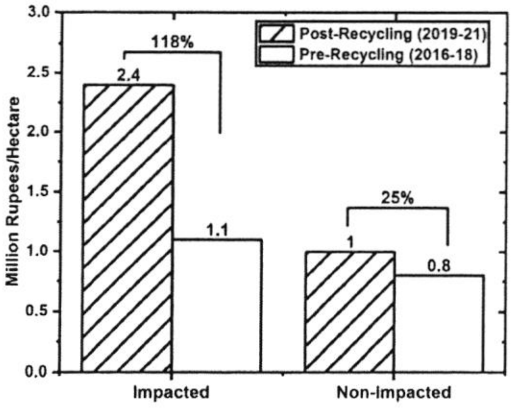

Fig. 9. Change in the value of agricultural land between pre- to post-recycling period
Source: Household survey.

3.4.8. *Impact on overall income*

3.4.8.1. Comparison between impacted and non-impacted areas. Table 6 indicates that the average net income of farmers was relatively higher in impacted areas compared to non-impacted areas. For instance, the average income from flower cultivation was Rs. 2,27,893/ha in impacted areas whereas Rs. 75,345/ha in non-impacted areas, indicating an increase of 202 %. Similarly, average income from vegetable, plantation and cereals cultivation was also relatively high at Rs. 6,54,672/ha, Rs. 3,72,583/ha and Rs. 49,372/ha in impacted areas compared to Rs. 2,62,143/ha, Rs. 1,93,790/ha and Rs. 32,352/ha at the non-impacted areas, indicating increase of 150 %, 92 % and 53 % respectively. Recourse to multiple cropping as well as increased agricultural crop yields is together responsible for this increase.

It was observed that the average income from livestock was substantially high at Rs. 1,29,200/farm in impacted areas compared to Rs. 93,245/farm in non-impacted areas, indicating an increase of 38 %. Similarly, it was observed that average income from non-farm activities was also relatively higher in impacted areas. Data from multiple sectors reveals that water availability and the increased GW table are playing an important role in the radical improvement of the agro-economic system.

3.4.9. *Impact on asset creation - recent purchases of essential and non-essential goods*

Table 7 indicates an improvement in the buying pattern of various household goods and agricultural tools in impacted areas. There was a 3-fold increase in the purchase of new four-wheelers. Also, 42 sample farmers from the impacted areas refurbished their houses from "Kutcha" to "Pukka" status as compared to only 19 sample farmers from non-impacted areas. It indicates that an increase in income influenced the purchase behaviour in the sample areas. The positive relationship between socio-economic status and living standards along with the purchase of household goods is already well established (Slama and Tashchian, 1985; Karthika et al., 2015; Mashao and Sukdeo, 2018).

3.4.10. *Impact on public health*

Table 8 indicates that during the post-recycling period average incidence of water-borne diseases such as typhoid and cholera was reported lower at 3353 and 7 compared to the pre-recycling period with 3409 and 11, this indicates a decrease of 1.6 % and 36 % respectively, whereas the incidence of average diarrhea cases was reported slightly high during post-recycling (46) compared to the pre-recycling period (42). A major surge was reported in chikungunya (182 %) followed by dengue (83 %)

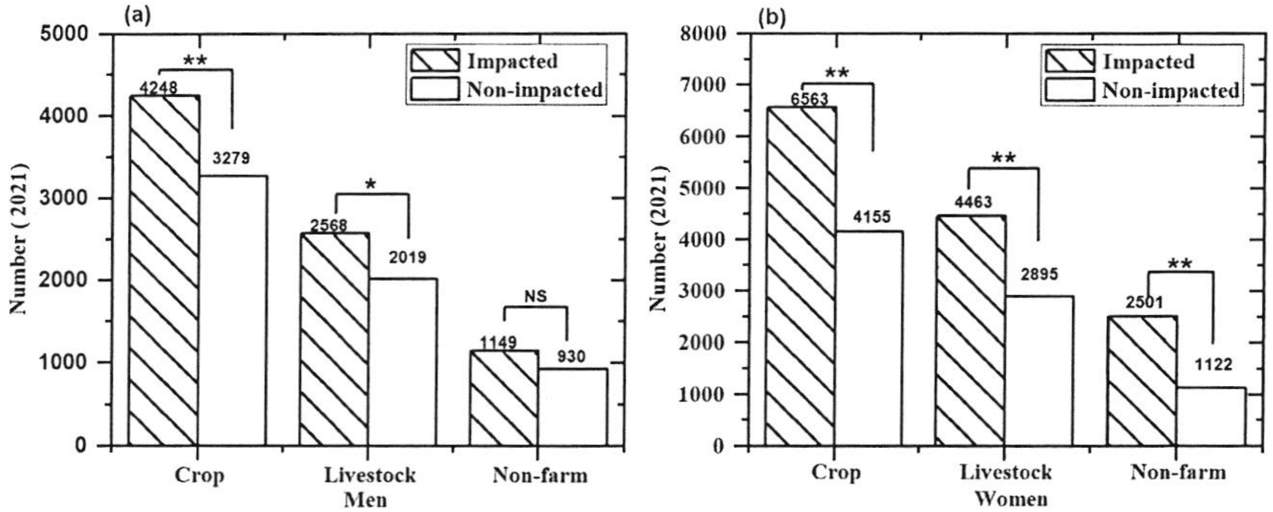

Fig. 10. Change in labour utilization pattern between impacted and non-impacted areas, (a) Men (b) Women.
Source: Household survey
Note: Student's *t*-test value (a) Crop (4.20), Livestock (2.38), Non-farm (1.19). (b) Crop (6.22), Livestock (40.05), Non-farm (4.39). Significant for $*p < 0.05$, $**p < 0.01$.

cases from the pre- to post-recycling period. The incidence of average leptospirosis cases was reported lower during the post-recycling period (5) compared to the pre-recycling period (7).

Over the past 2 years, a noticeable increase in the number of chikungunya and dengue cases was reported across the Karnataka state (www.statista.com) after a long period since India reported re-emerging of the chikungunya outbreak in 2005 (Jain et al., 2020; Sengupta et al., 2020; Sujatha, 2021). Experts from the health department revealed that the increasing numbers of mosquito-borne diseases are a direct consequence of the excess rainfall in the state over the last 2 years, resulting in an expanded pool of stagnant freshwater. This has led to the excess breeding of mosquitoes (Press Trust of India (PTI[a]), 2021) and therefore does not appear to be due to increased GW availability.

Data obtained from the household survey also confirmed that there was no noticeable increase in water-borne diseases in impacted areas compared to non-impacted areas. The occurrence of skin rashes and itching was reported by most of the farmers (80 %) in both the study areas. However, this is certain as a range of studies has established the relation between agricultural workers and skin diseases due to direct exposure to soil, plants, insects, pesticides, sunlight, heat, and infectious agents during farming (Susitaival, 2000; Donham and Thelin, 2016; Bashir et al., 2021).

As discussed in Section 3.2 as far as heavy metals are concerned their presence is below the permissible drinking water standards IS 10500 of India and as such does not pose any serious health risks. Analysis of the health reports for the district and household survey data indicate no increased incidents or chronic impacts due to the presence of chemical compounds in the STW (Sanchez and Egea, 2018; Yadav et al., 2021). However, in order to prevent an undiscovered public health hazard, direct use / contact with water present in tank is prohibited at this stage.

The surface water from the tanks filled with STW and rain-fed tanks in the same region i.e., tanks that did not receive STW but received only rainwater, as controls, were tested. Water in these tanks was studied for antibiotic resistance based on minimum inhibitory concentrations (MIC) of a few representative bacterial species. Resistance to antibiotics such as azithromycin, ciprofloxacin, cefotaxime, amoxicillin + clavulanic acid, cefotoxime + clavulanic acid, and meropenem was studied. These preliminary and ongoing studies indicate a predominance of higher resistance to azithromycin among all the tanks studied i.e., both controls and those receiving STW. However, there were no significant differences in antibiotic resistance levels between these two tanks. Further studies are being

Table 6
Change in income from different units of production between impacted and non-impacted areas.

Sl. No.	Income source in 2021	Impacted farmers (Rs/ha)	Non-impacted farmers (Rs/ha)	Percentage change (%)
I	Crops			
	Cereals	₹ 49,372	₹ 32,352	53
	Vegetables	₹ 6,54,672	₹ 2,62,143	150
	Pulses	₹ 98,027	₹ 93,552	5
	Plantation	₹ 3.72,583	₹ 1,93,790	92
	Flowers	₹ 2,27,893	₹ 75,345	202
II	Livestock	₹ 1,29,200	₹ 93,245	39
III	Non-farm income			
	Service	₹ 48,725	₹ 35,213	38
	Rental Income	₹ 62,352	₹ 27,822	124

Source: Household survey.

Table 7
Change in the new purchase of essential and non-essential goods between impacted and non-impacted areas.

New purchase/assets	Impacted areas	Non-impacted areas	Percentage change (%)
Year	2021	2021	
Household goods	Newly purchase	Newly purchase	
Refurbished house (Kutcha to Pakka)	42	19	121
TVs	62	60	3
Smart phones	163	105	55
Refrigerator	38	17	124
Washing machine	23	11	109
Sofa set	47	21	124
Two-wheeler	27	16	69
Four-wheeler	13	4	225
Agricultural tools			
Seed drill	18	11	64
Wooden plough	6	3	100
Tractor	25	12	108
Sprayer	37	19	95
Pump house	14	5	180
Drip or Sprinkler System	224	226	9
Cattel Shed	44	37	19
Harvesting machines	72	49	47
Seed drill	18	11	64

Source: Household survey.

Table 8
Change in the incidence of diseases between pre to the post-recycling period in the Kolar district.

Diseases	Pre-recycling (2016–18) (Average)	Post-recycling (2019–21) (Average)	Percentage change (%)
Dengue	96	176	83
Chikungunya	67	190	182
Typhoid	3409	3353	(−1.6)
Cholera	11	7	(−36)
Leptospirosis	7	5	(−28)
Diarrheal	42	46	10

Source: District surveillance Office, Kolar.

pursued to explain the generally high prevalence of antibiotic resistance among these water bodies (including control tanks). It has been reported that the strong prevalence of various detergents has triggered the expression of many antibiotic-resistance genes in various representative bacteria and needs further understanding (Khuntia et al., 2019; Khuntia and Chanakya, 2020). It is important to note that, these tanks receiving STW do not form drinking water sources for people in the region but are only used for indirect GW recharge.

3.4.11. *Impact on animal health*

Observations on major causes and number of animal deaths in the Kolar district are presented in Table 9. The most important change from increased water availability is the increased availability of green fodder and fodder in general leading to better animal nutrition. This is indirectly indicated by the increased level of livestock rearing as discussed earlier. The various other indicators of health, namely commonly occurring diseases and causes of animal deaths were documented in this survey. In general, there were only marginal changes in the pattern of causes of livestock mortality. The average number of cow mortalities was higher during the pre-recycling period (149) than in the post-recycling period (122). From the pre-to-post recycling period, the mortality from bloating and babesia decreased by 12 % and 36 % respectively. Among buffaloes, there were slightly lower mortality from most causes. It was also noted that cow mortality was higher than buffalo. The mortality from waterborne diseases was negligible in livestock animals since direct consumption of treated wastewater was restricted.

3.4.12. *Opinion of the sample farmers of impacted areas on the overall benefit of the availability of water in tanks*

According to Table 10, the overall opinion of the sample farmers on the availability of water in tanks was recorded. According to the results, 93 % of sample respondents claimed that the availability of water in tanks have a significant impact on agriculture production. According to 88 % of the farmers, GW levels increased substantially, 78 % noted an improvement in sanitation and hygiene, and 76 % said their incomes have increased. According to 67 % of respondents, cropping patterns have changed and there is now an option to grow multiple crops along with vegetables and flowers, 62 % reported that water availability and accessibility have increased, 59 % reported borewell rejuvenation, 58 % said that women empowerment has increased, 58 % claimed an increase in livestock rearing and milk production, 49 % confirmed about the rise in lifestyles and purchasing power and 43 % stated that fallow and barren land has been converted into fertile or productive lands. In the survey, 29 % reported that bird movement and migration increased and 21 % also informed that some of these farmers who had migrated to urban areas for employment have returned to the village and are now farming once again. This is a clear demonstration of reverse migration, an important indicator for improvements in the agricultural sector. This study provides empirical evidence that the K&C valley project has created the potential to improve the agro-economic situation, food security, and environmental aspects, thus building a circular economy, and has been documented in this study.

The study provides empirical evidence that treated wastewater in tanks increases agricultural activities and incomes. Results of this study support the findings of Pedrero et al. (2010), Sathaiah and Chandrasekaran (2020), Busaidi and Mushtaque (2017) which indicate a positive relation between using treated wastewater in agriculture and improvement in agricultural production. A study by Nandan et al. (2021) reveals that the availability of water in tanks increases the GW table, agricultural production, and socio-economic development while reducing the power consumption in water-scarce regions of Telangana state.

4. Conclusion and policy recommendation

The present study quantifies the socioeconomic impacts of the large-scale secondary treated wastewater (STW) from an urban city to neighbouring areas. About 440 MLD of STW from Bengaluru was pumped to Kolar to fill 137 existing surface water tanks to achieve indirect GW recharge. The results show that the STW in the surface water tanks complies with the most stringent standards set by India's The Hon'ble NGT and three important criteria of CPCB's "designated best uses of water" i.e., bathing water quality (B), wild-life propagation and fisheries management (D), and irrigation (E). As a consequence of this project, the surface tanks receiving water have now become a hotspot for biodiversity, with rapid improvement in fish production and bird movement. Outcomes of this study have revealed a greater range of benefits in impacted areas, such as replenishment of GW table, rejuvenation of borewells and open-wells, and improved water security. Significant improvements were observed in crop productivity (flower-80 %, vegetables-70 %, plantation-36 %, and fruits-35 %), an extension of the cropping season, an increase in livestock rearing (cattle-37 % and buffalo-33 %), milk production (Bangarpete- 37 %, Mulbagal- 25 % and Kolar-17 %), land value (118 %) and income. This project has created new job opportunities and reverse migration from urban to rural areas. Improvements in agricultural activities also led to an increase in on-farm employment opportunities for women, which in turn had an impact on decision-making in all domestic spheres. No direct negative effects were reported on public and animal health as a result of GW recharge. Whereas it is recommended to investigate long term impacts of indirect groundwater recharge further deeply through STW on public health in the studied population as usually, they are bio-accumulating.

Similar to Jakkur and Puttenahalli in Bengaluru (which received treated wastewater) (Inayathulla and Paul, 2013; Ramachandra et al., 2020; Pinglay, 2021), this initiative has also become a model for a

Table 9
Major causes and number of animal death in the Kolar district.

Diseases	Cow (Average)			Buffalos (Average)		
	Pre-recycling (2016–18)	Post-recycling (2019–21)	Percentage change (%)	Pre-recycling (2016–18)	Post-recycling (2019–21)	Percentage change (%)
Bloating	80	71	(−12)	6	5	(−17)
Babiosis	30	19	(−36)	2	1	(−50)
Other diseases*	39	32	(−18)	11	7	(−36)
Total	149	122	(−18)	19	13	(−31)

Source: Department of Veterinary Sciences, Kolar.
Note: Other diseases-Anaplasmosis, Downer cow syndrome, Choke, Food/plant poisonings.

Table 10

Opinion of the sample farmers of impacted areas on the overall benefit of treated wastewater stored in tanks.

Particulars	Yes (%)	Particulars	Yes (%)
Agricultural production increased	93	Employment of women increased	58
Groundwater level increased	88	Change in livestock pattern	58
Sanitation, hygiene and cleanliness of surrounding areas improved	78	Increased in milk production	58
Income increased	76	Lifestyle improved	49
Crop pattern changed (multiple crop/vegetables)	67	Transformation of bare land to productive land	43
Easy accessibility of water	62	Bird movement/migratory bird	29
Borewell started functioning or properly functioning	59	Rural migration	21

Source: Household survey.

waste water management system that allows GW recharge and biodiversity to be enhanced. In addition to enabling a transition from urban to rural water recycling, this project contributes to the transition towards the circular economy in the water sector, which is beneficial at several levels: economics, environment, social and cultural. The availability of water in tanks facilitates local recharge throughout the year and rejuvenation of borewells provides support to small and marginal farmers who cannot afford to deepen borewells or pay the cost of the declining GW table.

To shorten the gaps between water supply and demand, the results of this study will eventually help the different stakeholders including central, state, district, and local government authorities to draft and implement policies to encourage integrated planning, and management of wastewater reuse for GW recharge. This in turn has a sustainable approach to resolving water crises and has a high potential to improve the agro-economic system and food security. The establishment of a proper monitoring system awareness and training program among farmers about the selection of crop patterns, fertilizer use, and irrigation technique must be in place for a sustainable outcome. The involvement of the community in decision-making, planning, and implementation is also vital for the success of the project. To promote the reuse of recycled water, a public-private partnership (PPP) should be established, similar to the Nagpur model (Press Trust of India (PTIb), 2021), in which 90 % of wastewater was reused. Furthermore, it illustrates how PPP can enhance water security and reduce wastewater burden by reusing treated wastewater.

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CRediT authorship contribution statement

Manjari Manisha – Corresponding Author, study design, data collection, analysis, designing and drafting of the manuscript.

Kavita Verma – Study design, analysis and drafting.

Ramesh N – Data collection, designing of the manuscript.

Anirudha TP – Data collection, designing of the manuscript.

Santrupt RM – Data collection, designing of the manuscript.

Reshmi Das – Data collection.

Mohan Kumar MS – Conception, designing of the study and review of the article.

Chanakya HN – Conception, designing of the study and review of the article.

Lakshminarayana Rao – Conception, designing of the study and review of the article.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abusam, A., Shahalam, A., 2013. Wastewater reuse in Kuwait: opportunities and constraints. WIT Trans. Ecol. Environ. 179, 745–754.

Aleisa, E., 2019. Analysis on reclamation and reuse of wastewater in Kuwait. J. Eng. Res. 7 (1).

Aly Gondia, M.K., Bakr, M., Mohamed, A.G., 2021. Sustainable management of treated wastewater, the New El-Mahsama wastewater treatment plant in Sinai. J. Environ. Treat. Tech. 9 (4), 804–814.

APHA, 2005. Standard Methods for the Examination of Water and Wastewater. 21st edition. American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC.

Arkin, H., Colton, R.R., 1950. Tables for Statisticians. Barnes and Noble Publication New.

ARMCAN, ANECC, NHMRC, Agriculture and Resource Management Council of Australia and New Zealand, Australian and New Zealand Environment and Conservation Council, National Health and Medical Research Council, 2000. National Water Quality Management Strategy. Guidelines for Sewerage Systems: Use of Reclaimed Water, Australia Available at: use-reclaimed-water.pdf (waterquality.gov.au).

Asano, T., Cotruvo, J.A., 2004. Groundwater recharge with reclaimed municipal wastewater: health and regulatory considerations. Water Res. 38 (8), 1941–1951.

Ballukraya, P.N., 1997. Groundwater over exploitation: a case study from Moje-Anepura, Kolar District, Karnataka. J. Geol. Soc. India 50 (3).

Bashir, S., Hassan, I., Wani, R.T., Zeerak, S., Shah, F.Y., 2021. Pattern of skin diseases and occupational dermatoses among paddy field workers in Kashmir Valley: a cross-sectional study from North India. Indian J. Community Med. 46 (4), 610–613.

Bekele, E., Toze, S., Patterson, B., Higginson, S., 2011. Managed aquifer recharge of treated wastewater: water quality changes resulting from infiltration through the vadose zone. Water Res. 45 (17), 5764–5772.

Bekele, E., Toze, S., Patterson, B., Fegg, W., Shackleton, M., Higginson, S., 2013. Evaluating two infiltration gallery designs for managed aquifer recharge using secondary treated wastewater. J. Environ. Manag. 117, 115–120.

Bera, B., Shit, P.K., Sengupta, N., Saha, S., Bhattacharjee, S., 2022. Steady declining trend of groundwater table and severe water crisis in unconfined hard rock aquifers in extended part of Chota Nagpur Plateau, India. Appl. Water Sci. 12 (3), 1–19.

Biswas, A.K., Hartley, K., 2017. From evidence to policy in India's groundwater crisis. The Diplomat.

Busaidi, A.A., Mushtaque, A., 2017. Maximum use of treated wastewater in agriculture. Water Resources in Arid Areas: The Way Forward. Springer International Publishing AG.

Chindarkar, N., Grafton, R.Q., 2019. India's depleting groundwater: when science meets policy. Asia Pac. Policy Stud. 6 (1), 108–124.

CGWB, Central ground water board, 2016. Kolar taluk aquifer maps and management plans, Kolar district, Karnataka. Available at http://cgwb.gov.in/AQM/NAQUIM_REPORT/karnataka/Kolar.pdf.

NEERI, National Environmental Engineering Research Institute, 2015. Available at: Project Completed, Page - 4 - Water Technology and Management Division/The Official Website of CSIR-National Environmental Engineering Research Institute, Government of India.

CPCB Central Polution Control Board, 2013. Available at Designated_Best_Use_Water_Quality_Criteria.pdf (cpcb.nic.in).

Dangar, S., Asoka, A., Mishra, V., 2021. Causes and implications of groundwater depletion in India: a review. J. Hydrol. 596.

Deepa, K., Krishnaveni, M., 2012. Water quality performance of sol aquifer treatment (SAT) using municipal treated wastewater of Chennai city, India. J. Environ. Hydrol. 20 (2).

DEIAA, 2020. District Mineral Survey Report of Kolar District, Karnataka, Mines & Geology Department, Kolar. Available at. http://environmentclearance.nic.in/DownloadPfdFile.aspx?FileName=LkHrLg8Xn4+eAty6Za7l/uwq0QkttR/iZTn7mkRY0XTMLHWQS2uF789q9Y5eKhfEDJUlVvOIdzcaZ2OfurVB3g==&FilePath=93ZZBm8LWEXfg+HAlQix2fE2t8z/pgnoBhDlYdZCxzVPEh4a7F53Cae7tleKGoXIDiA7chYePNgRJpehWx3dLsaLaee8RS5VxBvVdCAnIMg=.

Department of Fishery Sciences, Kolar, 2021. Available at: http://www.fisheries-kolar.com/.

Dillon, P., Arshad, M., 2016. Managed aquifer recharge in integrated water resource management. Integrated Groundwater Management. Springer, Cham, pp. 435–452.

Djamel, G., Noureddine, E., Abdulaziz, A., 2019. Direct potable reuse: the Singapore NEWater Project as a role model. Open Access Libr.J. 6, 1–11.

Donham, K.J., Thelin, A., 2016. Agricultural Skin Diseases. Handbook: Agricultural Medicine: Rural Occupational and Environmental Health, Safety, and Prevention, Second edition John Wiley & Sons, Inc., pp. 155–179.

Engberg-Pedersen, Lars, 2011. Coping With Poverty and Institutionalised Practices: Tank-Irrigated Cultivation in Kolar District, Karnataka. DIS Working Paper.

Essandoh, H.M., Tizaoui, C., Mohamed, M.H., Amy, G., Brdjanovic, D., 2011. Soil aquifer treatment of artificial wastewater under saturated conditions. Water Res. 45 (14), 4211–4226.

Garg, K.K., Anantha, K.H., Nune, R., Akuraju, V.R., Singh, P., Krishna, G.M., Dixit, S., Ragab, R., 2020. Impact of land use changes and management practices on groundwater resources in Kolar district, Southern India. J. Hydrol. Reg. Stud. 31 (100732).

GoK (Government of Karnataka), 2016. District Irrigation Plan – Kolar District. Pradhana Mantri Krishi Sinchayee Yojane (PMKSY) Available at: PMKSY.

Icekson-Tal, N., Avraham, O., Sack, J., Cikure H., I., 2003. Water reuse in Israel - the Dan Region Project: evaluation of water quality and reliability of plant's operation. Water Supply 3 (4), 231–237.

Inayathulla, M., Paul, M.J., 2013. Assessment of surface water chemistry of Jakkur Lake. Bangalore, Karnataka, India. Int. J. Sci. Eng. Res. 4 (5), 302–305.

Jain, J., Kaur, N., Haller, S.L., Kumar, A., Rossi, S.L., Narayanan, V., 2020. Chikungunya outbreaks in India: a prospective study comparing neutralization and sequelae during two outbreaks in 2010 and 2016. Am. J. Trop. Med. Hyg. 102, 857–868.

Jhansi, S.C., Mishra, S.K., 2013. Wastewater treatment and reuse: sustainability options. Consilience J. Sustain. Dev. 10 (1), 1–15.

Jodar-Abellan, A., López-Ortiz, M.I., Melgarejo-Moreno, J., 2019. Wastewater treatment and water reuse in Spain. Current situation and perspectives. Water 11 (8), 1551.

Kadam, P., Bhalerao, S., 2010. Sample size calculation. Int. J. Ayurveda Res. 1 (1), 55–57.

Kanarek, A., Michail, M., 1996. Groundwater recharge with municipal effluent: Dan region reclamation project, Israel. Water Sci. Technol. 34 (11), 227–233.

Karthika, R., Anand, N.V., Chandrakhanthan, J., 2015. A study on consumer behaviour towards household goods in Tiruchirapalli District. Aust. J. Basic Appl. Sci. 9 (23), 22–27.

Kesari, K.K., Soni, R., Jamal, Q.M.S., 2021. Wastewater treatment and reuse: review of its applications and health implications. Water Air Soil Pollut. 232, 208.

Khuntia, H.K., Chanakya, H.N., 2020. Accumulation of antibiotic-resistant genes in anaerobic biofilm reactor fed with household chemical products. SN Appl.Sci. 2 (8), 1–7.

Khuntia, H.K., Chandrashekar, S., Chanakya, H.N., 2019. Treatment of household greywater laden with household chemical products in a multi-chambered anaerobic biofilm reactor. Sustain. Cities Soc. 51, 101783.

Kochar, A., Nagabhushana, C., Sarkar, R., Shah, R., Singh, G., 2022. Financial Access and Women's Role in Household Decisions: Empirical Evidence From India's National Rural Livelihoods Project.

Kog, Y.C., 2020. Water reclamation and reuse in Singapore. J. Environ. Eng. 146 (4), 03120001.

Kolar district profile, 2009. Ground Water Information Booklet Available at: Microsoft Word - KOLAR_BROCHURE.doc (cgwb.gov.in).

Lawton, J., Hallowell, N., Snowdon, C., 2017. Written versus verbal consent: a qualitative study of stakeholder views of consent procedures used at the time of recruitment into a peripartum trial conducted in an emergency setting. BMC Med. Ethics 18, 36. https://doi.org/10.1186/s12910-017-0196-7.

Lohani, M., Aburaida, L., 2017. Women empowerment: a key to sustainable development. Soc.ION 6 (26), 9886095465.

Mashao, E.T., Sukdeo, N., 2018. Factors That Influence Consumer Behaviour in the Purchase of Durable Household Products. Conference Paper, IEOM.

Mazari-Hiriart, M., Ponce-de-Leon, S., Lopez-Vidal, Y., Islas-Macias, P., Amieva-Fernández, R.I., Quiñones-Falconi, F., 2008. Microbiological implications of periurban agriculture and water reuse in Mexico City. PLoS One 3 (5), e2305.

Minhas, P.S., Saha, J.K., Dotaniya, M.L., Sarkar, A., Saha, M., 2022. Wastewater irrigation in India: current status, impacts and response options. Sci. Total Environ. 808.

Nagaraj, N., Chandrashekhar, H., Yatheesh, H.S., 2003. Sustainability and equity implication of groundwater depletion in hard rock areas of Karnataka-an economic analysis. Ind. J. Agric. Econ. 58, 438–447.

Nandan, M.J., Surinaidu, L., Kumar, D., 2021. Sustainable irrigation and economic development through community participated managed aquifer recharge in water scarce regions of Telangana state — a case study. J. Geol. Soc. India 97, 1294–1299.

Narain-Ford, D.M., Bartholomeus, R.P., Dekker, S.C., Wezel, A.P.V., 2020. Natural purification through soils: risks and opportunities of sewage effluent reuse in sub-surface irrigation. Rev. Environ. Contam. Toxicol. 250, 85–117.

NGT, National Green Tribunal, 2019. Available at https://greentribunal.gov.in/sites/default/files/all_documents/4th-report-alongwith-annexures_compressed.pdf.

Ofori, S., Puskacova, A., Ruzickova, I., Wanner, J., 2021. Treated wastewater reuse for irrigation: pros and cons. Sci. Total Environ. 760.

Okello, C., Tomasello, B., Greggio, N., Wambiji, N., Antonellini, M., 2015. Impact of population growth and climate change on the freshwater resources of Lamu Island, Kenya. Water 7 (3), 1264–1290.

Packialakshmi, S., Balaji, S., Kumaresan, T., 2015. Inducing recharge of groundwater by treated wastewater—a pilot study in Southern Chennai Metropolitan Area. Indian J. Sci. Technol. 8 (11).

Pandey, P., Choubey, A.K., Rai, G., 2021. The involvement of women as the domestic decision maker: a study of Patna Metropolitan City, Bihar, India. Soc. Nat. 33, e62053.

Partyka, M.L., Ronald, F.B., 2022. Wastewater reuse for irrigation of produce: a review of research, regulations, and risks. Sci. Total Environ. 828.

Pedrero, F., Kalavrouziotis, I., Alarcón, J.J., Koukoulakis, P., Asano, T., 2010. Use of treated municipal wastewater in irrigated agriculture—review of some practices in Spain and Greece. Agric. Water Manag. 97 (9), 1233–1241.

Pinglay, P., 2021. Available at: The Story of Jakkur Lake Sets an Example for Inclusive Rejuvenation Projects - Vikalp Sangam.

Press Trust of India (PTIa), 2021. Available at: Heavy Rainfall Triggering Rise in Dengue Cases in Karnataka | Deccan Herald.

Press Trust of India (PTIb), 2021. Available at: India's 1st and Largest PPP on Waste Water Reuse Completed in Record Time During Pandemic; Bags FICCI Water Award 2020 | Business Standard News (business-standard.com).

Ramachandra, T.V., Varghese Sincy, K.S., Asulabha, 2020. Efficacy of rejuvenation of lakes in Bengaluru, India. Green Chem. Technol. Lett. 6, 14–26.

Ramaiah, S.N., Reddy, R., Reddy, V.J., 2017. Over-exploitation of groundwater, and its impact on phreatic aquifer system, surface water bodies and rural water supply schemes in Malur Taluk, Kolar District, Karnataka - a case study. Nat. Environ. Pollut. Technol. 16, 599–605.

Rao, H., Rao, L., Chanakya, H.N., 2021. Fate of heavy metals in sewage and polluted water bodies. Curr. Sci. 121 (1), 109.

Rondhi, M., Pratiwi, P.A., Handini, V.T., Sunartomo, A.F., Budiman, S.A., 2018. Agricultural land conversion, land economic value, and sustainable agriculture: a case study in East Java, Indonesia. Land 7, 148.

Roy, D., Palavalli, B., Menon, N., 2018. Survey-based socio-economic data from slums in Bangalore,India. Sci. Data 5, 170200. https://doi.org/10.1038/sdata.2017.200.

Sanchez, W., Egea, E., 2018. Health and environmental risks associated with emerging pollutants and novel green processes. Environ. Sci. Pollut. Res. 25, 6085–6086.

Sathaiah, M., Chandrasekaran, M., 2020. A bio-physical and socio-economic impact analysis of using industrial treated wastewater in agriculture in Tamil Nadu, India. Agric. Water Manag. 241 (4).

Sengupta, S., Mukherjee, S., Haldar, S.K., Bhattacharya, N., Tripathi, A., 2020. Re-emergence of Chikungunya virus infection in Eastern India. Braz. J. Microbiol. 51 (1), 177–182.

Shan, V., Singh, S.K., Haritash, A.K., 2020. Water crisis in the Asian countries: status and future trends. Resilience, Response, and Risk in Water Systems, pp. 173–194.

Shawaqfah, M., Almomani, F., Al-Rousan, T., 2021. Potential use of treated wastewater as groundwater recharge using GIS techniques and modeling tools in Dhuleil-Halabat well-field/Jordan. Water 13 (11), 1581.

Singh, U.V., 2020. The recycling of sewage generated in Kormanagala-Chellaghtta valley of Bengaluru India. Adv. Environ. Waste Manag. Recycl. (ISSN: 2641-1784) 3 (2), 47–62.

Slama, M.E., Tashchian, A., 1985. Selected socioeconomic and demographic characteristics associated with purchasing involvement. J. Market. 49 (1), 72–82.

Suhag, R., 2016. Overview of ground water in India. PRS Legis.Res. 9504 (February), 12.

Sujatha, S., 2021. Current status of Chikungunya in India. Front. Microbiol. 12 (3).

Susitaival, P., 2000. Occupational Skin Diseases in Farmers and Farm Workers Kanerva.

Theregowda, R.B., Alejandra, M.G., Ma, Xin Cissy, Garland, J., 2019. Nutrient recovery from municipal wastewater for sustainable food production systems: an alternative to traditional fertilizers. Environ. Eng. Sci. 36 (7), 833–842.

Tortajada, C., Bindal, I., 2020. Water Reuse in Singapore: The New Frontier in a Framework of a Circular Economy. Water Reuse Within a Circular Economy Contex, 2 Available at: Water_reuse_in_Singapore_The_new_frontier_in_a_framework_of_a_circular_economy-with-cover-page-v2.pdf (d1wqtxts1xzle7.cloudfront.net).

Tymchuk, I., Shkvirko, O., Sakalova, H., 2020. Wastewater a source of nutrients for crops growth and development. J. Ecol. Eng. 21 (5), 88–96.

Vehovar, V., Lozar-Manfreda, K., 2008. Overview: Online Surveys. The Sage Handbook of Online Research Methods.

Vivekananda, G.N., Swathi, R., Sujith, L.N., 2021. Multi-temporal image analysis for LULC classification and change detection. Eur. J. Remote Sens. 54 (sup2), 189–199. https://doi.org/10.1080/22797254.2020.1771215 York, pp. 1-10.

WHO, World Health Organization, 2006. Guidelines for the Safe Use of Wastewater, Excreta and Greywater. Geneva. Available at: who.int.

World Bank, 2010. Deep Wells and Prudence; Towards Pragmatic Action for Addressing Groundwater Over Exploitation in India D.C.Washigton.

World Bank, 2012. India Groundwater: A Valuable But Diminishing Resource.

World Bank, 2018. Wastewater: From Waste to Resource The Case of Atotonilco de Tula, Mexico Available at: World Bank Document.

Yadav, D., Rangabhashiyam, S., Verma, P., Singh, P., Devi, P., Kumar, P., Kumar, K.S., 2021. Environmental and health impacts of contaminants of emerging concerns: recent treatment challenges and approaches. Chemosphere 272, 129492.

Zaibel, I., Zilberg, D., 2021. Treated municipal wastewater as a water source for sustainable aquaculture: a review. Rev. Aquac. 14 (4).

Zaibel, I., Appelbaum, Y., Arnon, S., Britzi, M., Schwartsburd, F., Snyder, S., Zilberg, D., 2019. The effect of tertiary treated wastewater on fish growth and health: laboratory-scale experiment with Poecilia reticulata (guppy). PloS one 14 (6), e0217927.

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Assessing groundwater recharge rates, water quality changes, and agricultural impacts of large-scale water recycling

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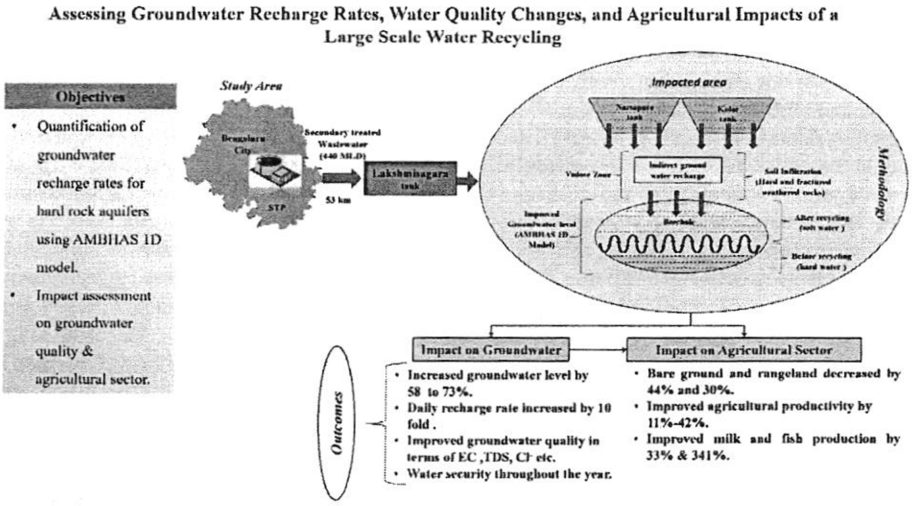
HIGHLIGHTS

- 10× improvement in daily groundwater recharge rates
- Groundwater levels increased by 58 % to 73 %
- Groundwater quality improved due to higher groundwater infiltration
- Significant improvement in agricultural productivity
- Sustainable solution for freshwater security and wastewater management

GRAPHICAL ABSTRACT



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ABSTRACT

The over-exploitation and insufficient replenishment of groundwater (GW) have resulted in a pressing need to conserve freshwater and reuse of treated wastewater. To address this issue, the Government of Karnataka launched a large-scale recycling (440 million liters/day) scheme to indirectly recharge GW using secondary treated municipal wastewater (STW) in drought-prone areas of Kolar district in southern India. This recycling employs soil aquifer treatment (SAT) technology, which involves filling surface run-off tanks with STW that intentionally infiltrate and recharge aquifers. This study quantifies the impact of STW recycling on GW recharge rates, levels, and quality in the crystalline aquifers of peninsular India. The study area is characterized by hard rock aquifers with fractured gneiss, granites, schists, and highly fractured weathered rocks. The agricultural impacts of the improved GW table are also quantified

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Abbreviations: APHA, American Public Health Association; ARB, Antibiotic Resistance Bacteria; BCM, Billion Cubic Meters; BIS, Bureau Indian Standard; BWSSB, Bengaluru Water Supply and Sewerage Board; CGWB, Central Ground Water Board; DEIAA, District Level Environment Impact Assessment Authority; ESRI, Environmental Systems Research Institute; GoK, Government of Karnataka; GW, Groundwater; ICPMS, Inductively Coupled Plasma Mass Spectrometry; K&C, Kormangala and Challaghatta; KGWA, Karnataka Groundwater Authority; KSNDMC, Karnataka State Natural Disaster Monitoring Centre; KSPCB, Karnataka State Pollution Control Board; LCMS, Liquid Chromatography- Mass Spectrometry; MAR, Managed Aquifer Recharge; MI & GW, Minor Irrigation and Groundwater; MLD, Million Liters per Day; NGT, National Green Tribunal; SAT, Soil Aquifer Treatment; STP, Sewage Treatment Plant; STW, Secondary Treated Wastewater.

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by comparing areas receiving STW to those not receiving it, and changes before and after STW recycling were measured. The AMBHAS_1D model was used to estimate the recharge rates and showed a tenfold increase in daily recharge rates, resulting in a significant increase in the GW levels. The results indicate that the surface water in the rejuvenated tanks meets the country's stringent water discharge standards for STW. The GW levels of the studied boreholes increased by 58–73 %, and the GW quality improved significantly, turning hard water into soft water. Land use land cover studies confirmed an increase in the number of water bodies, trees, and cultivated land. The availability of GW significantly improved agricultural productivity (11–42 %), milk productivity (33 %), and fish productivity (341 %). The study's outcomes are expected to serve as a role model for the rest of Indian metro cities and demonstrate the potential of reusing STW to achieve a circular economy and a water-resilient system.

1. Introduction

An increasing global population, industrial growth, urbanization, land use changes, and limited precipitation have caused a worldwide scarcity of freshwater, putting pressure on groundwater (GW) resources (Modrzynski et al., 2021; McCance et al., 2020; Wakode et al., 2018; Okello et al., 2015). India is the largest user of GW, with over 50 % of its rural population relying on it for basic needs (Garg et al., 2022). It is estimated that 17 % of India is overexploited due to excessive extraction of GW (58–65 % in 2020), reducing annual recharge from 447 billion cubic meters to 432 BCM (Dangar et al., 2021; GoI, 2021; CGWB, 2020; Hussain et al., 2017). To prevent further depletion, long-term water management strategies are crucial, with artificial GW recharge methods such as the use of rainwater and treated wastewater for improving the GW table. (Chen et al., 2023; Dihan et al., 2023; Manisha et al., 2023; Dillon and Arshad, 2016). Managed aquifer recharge (MAR) is a common technique for preserving GW by intentionally infiltrating water from the surface into GW and addressing freshwater scarcity (Sunyer-Caldú et al., 2023; Alam et al., 2021; Grinshpan et al., 2021; Ganot et al., 2018). MAR is achieved through techniques such as percolation tanks, rainwater harvesting, soil aquifer treatment (SAT), and infiltration basins (Alam et al., 2021).

SAT is a globally practiced wastewater recycling method under MAR that converts wastewater into high-quality recharge effluent by removing contaminants as wastewater infiltrates through soil layers (Grinshpan et al., 2021; Wei et al., 2015; Rahman et al., 2012; Icekson-Tal et al., 2003). Successful GW recharge schemes based on SAT are summarised in Table 1. The reported GW recharge rate, soil type, and changes in GW quality are also tabulated in Table 1. As can be seen from Table 1, GW recharge rates vary significantly even in sandy and sandy loamy soils, from 13.2 mm/day to 110 mm/day, with varying degrees of GW quality improvement. GW recharge rates and changes in GW quality are influenced by many factors such as soil type, soil permeability, local hydrogeology, heterogenicity, topography, land use, and management practices including GW pumping, and climatic conditions (Ramaiah et al., 2017). Very few studies investigated the effect of GW recharge through surface tanks in India on GW levels and quality (Nandanwar et al., 2020; Siva Prasad and Venkateswara Rao, 2018; Patil et al., 2017; Packialakshmi et al., 2015; NEERI, 2015). There is a lack of quantitative information in the literature on recharge rates in hard aquifers, effect on GW quality, and agricultural impact, especially for crystalline aquifers characterized by hard rock with fractured gneiss, granites, schists, and highly fractured weathered rocks of peninsular India. This study fills this gap and provides valuable insights into the effectiveness of large-scale water recycling in rural areas.

Recently, India has started large-scale recycling (Koramangala-Challaghatta valley project) of 440 million liters per day (MLD) of secondary treated wastewater (STW) based on SAT method (unlined and no wet/dry cycle) in Kolar district of Karnataka India. Kolar is a semi-arid drought-prone region with a normal annual rainfall of 650 mm for the period 1981 to 2010 (GoK, 2016; CGWB, 2009; KSNDMC, 2009). Kolar district had approximately four thousand unlined cascading man-made tanks or water reservoirs for capturing rainwater and were used for various purposes along with GW recharge (Engberg-Pedersen, 2011). With little or no rains over the last 10 years, numerous tanks and borewells had gone dry and the GW table declined at alarming levels due to over-exploitation (CGWB, 2020). The depth of irrigation borehole wells had reached ~250–300 m from the surface (Garg et al., 2020). Thus, to provide relief to the droughts, for effective management of the limited GW resources, and to ensure its long-term sustainability, in 2018, the Minor Irrigation and Groundwater

Table 1
Summary of SAT based groundwater recharge studies.

Sl. No.	Country	Climate	Soil type	Aquifer type	Wet/dry ratio	GW recharge rate (mm/day)	Impact on GW quality	Remarks	Reference
1.	Israel	Arid-semiarid	Sandy loamy	Sandy	0.5	13.3	• 70 % removal efficiency for TSS, COD, BOD, ammonia, nitrogen, phosphorous, and turbidity • 100 % removal of Coliform	• Recharged water: a reliable source of irrigation	Icekson-Tal et al., 2003
2.	Egypt	Dry-deserted	Sandy	Unconfined	0.5	25–35	• COD reduction by 95 % • BOD reduction by 70–80 %	• Constant hydraulic rate increases recharge rate by 40 %	El Arabi and Dawoud, 2012
3.	South Africa	Arid-semiarid	Sandy loamy	Sandy	–	26	• Not reported	• The numerical model MODFLOW for groundwater flow and contaminant transport	Jovanovic et al., 2017
4.	Australia	Semiarid/desert	Sandy-clay	Alluvial	0.33	107	• Improvement in recharged water quality in terms of EC, OC, TN, and $CaCO_3$	• Infiltration rates per basin varied from 0.1 to 1 m/day	Barry et al., 2017
5.	Belgium	Maritime	Sandy	Dune (saline)	–	110	• Improved water quality in terms of EC, TOC, hardness, chlorides, nitrates, phosphates, and heavy metals. Absence of total coliforms and pathogens.	• A unified conceptual model was developed, making a framework for forecasting long-term groundwater sustainability	Van Houtte and Verbauwhede, 2012
6.	Phoenix (USA)	Dry-deserted	Sandy	One layer, alluvial	0.75	Not reported	• Reduction in N by 65 %, faecal coliform by 99 %, TOC by 93 %	• Hydraulic loading rate 60–100 m/yr	Crites et al., 2014; Bauwer H., 1991

Development Department of the Government of Karnataka implemented large-scale recycling to fill 137 of these tanks with 440 MLD of STW coming from two sewage treatment plants (STPs) of Bangalore, (Manisha et al., 2023). The recycling was aimed to improve the GW table and GW quality by storing water in the existing tanks (Manisha et al., 2023; Singh, 2020). To the best of author's knowledge, there are no such large-scale full-fledged field implementation studies available in India wherein STW coming from major urban cities is used for the rejuvenation of existing surface tanks and subsequently facilitating indirect GW recharge in the semiarid drought-effective rural district. Hence, for the first time, this work (i) quantifies the GW recharge rates in the crystalline aquifers of peninsular India, characterized by hard rock aquifers with fractured weathered rocks using AMBHAS 1D GW modelling. (ii) Changes in GW quality due to the additional recharge from this project are also quantified, along with the impact on agriculture, fisheries, and milk production. (iii) Additionally, the social impacts of the improved GW table are quantified by comparing areas receiving STW to those not receiving it.

2. Methodology

2.1. Study area and design of large-scale recycling

Kolar district lies between north latitude 12° 45′ 54″ to 13° 35′ 47″ and east longitude 77° 50′ 29″ to 78° 35′ 18″ (CGWB, 2012; 2009) (Fig. 1). It has a total area of 3979 sq. km with a total population of 1,536,401(Census India, 2011). Kolar district falls under a partial rain shadow zone, and due to the topography and physiography, there are no perennial sources (rivers) of water. The soil is distributed in the range of red loamy to red sandy and lateritic soil (CGWB, 2020; DEIAA, 2019). Kolar predominantly has fractured multi-aquifer systems with gneiss/granite/schist rocks (GoK, 2016). Bedrock is peninsular gneiss of the archean age and the area can be classified as "hard rock terrain" (CGWB, 2020) with a semiarid climate. Nearly 60 % of the geographical area in the district is under agriculture which has a high-water demand (CGWB, 2020; DEIAA, 2019).

The recycling of STW in Kolar district was initiated in March 2018 (Manisha et al., 2023). The STW from Bangalore STPs is lifted and pumped first to Lakshmisagara tank (LT) of Kolar district which travels a distance of 53 km in closed channels. The water from this tank flows by gravity in open channels for a distance of 2 km to the Narsapura tank (NT) and from this tank, it flows from several ridge points to the rest of the other tanks including Kolar tank (KT). Kolar region has a network of cascading tanks that are connected by open channels. If the water level in an upstream tank exceeds its overflow weir, the excess water will flow into a downstream tank through these open channels, driven by natural gravity. These tanks are grouped into a total of 12 clusters based on their location and water flow network (a detailed plan of the recycling scheme and cluster classification along with the tank names is provided in Appendix A as Fig. A1 and Appendix B as B1 as the supplementary data). Only four pumping stations are installed in uphill areas where a gravity-based flow was not possible.

2.2. Secondary treated wastewater and surface tank water

STW samples were collected from the STP's outlet and stored at 4 °C in a refrigerator, before analysis. A detailed physio-chemical and microbiological analysis was carried out to estimate the water quality using standard methods for water and wastewater characterization (APHA, 2005). To analyse the overall impacts of this recycling, two surface tanks namely i) NT and ii) KT were selected as model tanks to represent 137 tanks. The tanks selected in the study were identified as having received STW at the start of the recycling. The NT was 2 km away from the very first tank i.e., LT whereas the KT was 16 km away from the NT (Fig. 2). A detailed water quality analysis as per the Hon'ble National Green Tribunal (NGT)

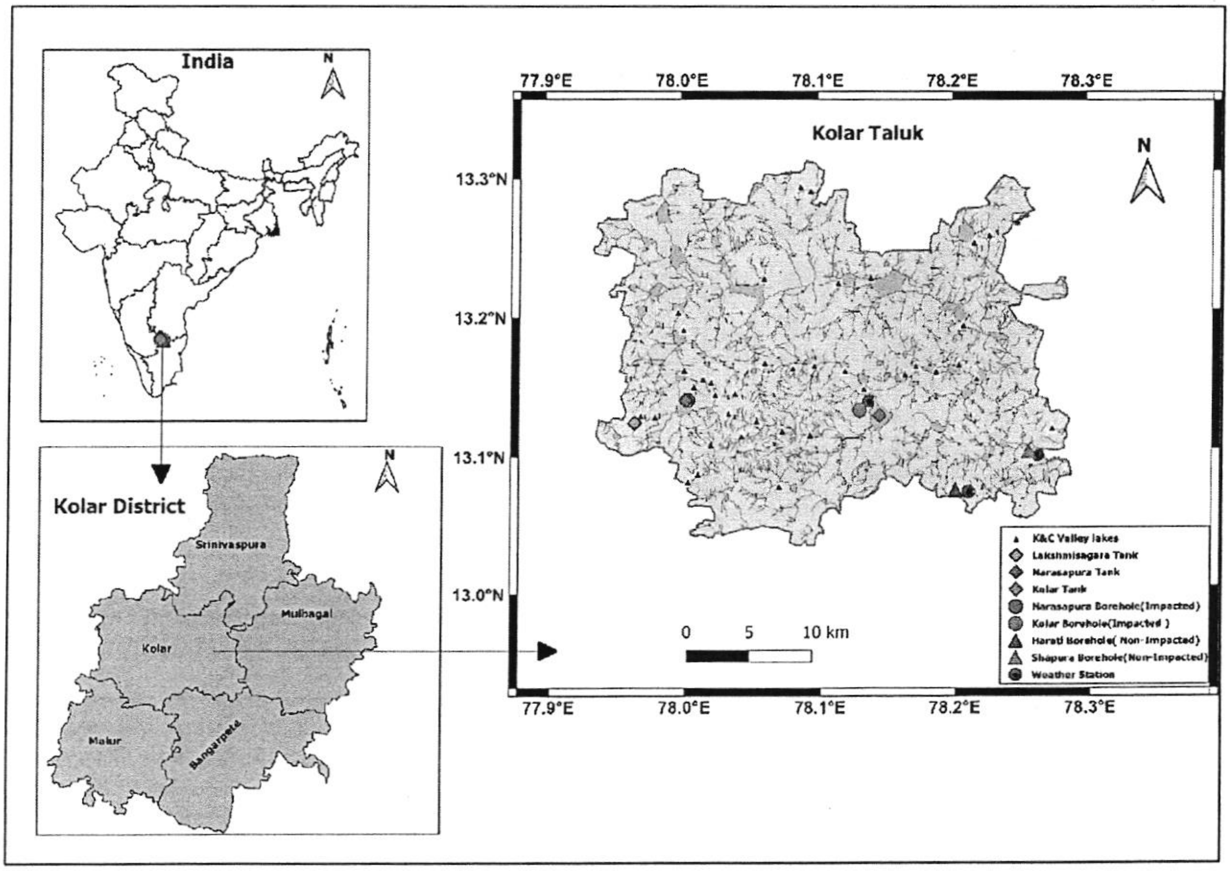

Fig. 1. Study area.

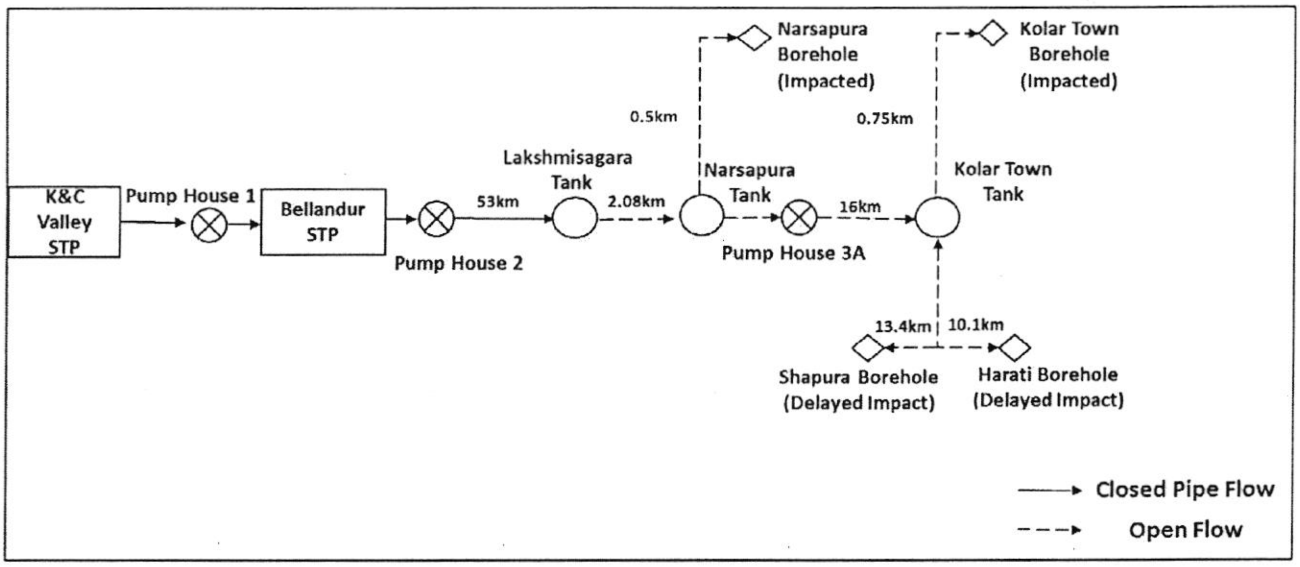

Fig. 2. Surface tank and groundwater sampling points.

standards (NGT and National Green Tribunal, 2019) which includes the specific eight parameters pH, biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), ammoniacal nitrogen (NH_4-N), total nitrogen (TN), phosphate phosphorus (PO_4-P), and faecal coliform was performed for the STW and surface water tanks. All the water samples were tested in triplicates and average values are represented with standard deviation as avg. ± std. dev. Other than the NGT parameters a detailed analysis for heavy metals and up to 10 emerging contaminants was also carried out for the STW and surface water of the first tank (LT) receiving the treated water. ICPMS (Quadrupole ICPM- Thermo X series II) that can operate in both analog and pulse counting modes (Awual and Hasan, 2015) was used for heavy metal analysis, and LCMS (Dionex Ultimate 3000 (Thermo), micro-LC equipped with C18, 150 × 4.6 mm, 5 μm reversed phase column for the analysis of emerging contaminants. The instrument sensitivity ranges between <10 ppb to <1 ppt (parts per thousand).

2.3. Groundwater

2.3.1. Sampling and characterization

To study the impact of indirect GW recharge using STW on GW quality two boreholes namely i) Narsapura (NB) and ii) Kolar town (KB) which were in the vicinity of the two selected surface tanks (NT and KT) were identified and designated as "impacted" boreholes. NB was 0.5 km from NT and KB was 0.75 km away from KT (Fig. 2). Similarly, two boreholes i) Shapura (SB) and ii) Harati (HB) were around 10–14 km away from one of the impacted tanks KT, were also sampled and was designated as delayed impact. The GW samples were collected and analysed following the standard methods (APHA, 2005) for their physio-chemical constituents such as pH, hardness, total dissolved solids (TDS), and electrical conductivity (EC). Calcium (Ca^+) and sodium (Na^+) as important cations, chlorides (Cl^-), and nitrates (NO_3^-) as anions, (Awual, 2016). Other water quality parameters such as magnesium (Mg^+), potassium (K^+), sulfate (SO_4^{2-}), and fluoride (F^-) were also measured using standard methods.

2.3.2. Historical groundwater level and water quality data

Historical data of GW levels and GW quality was collected to analyse the impacts of indirect GW recharge using STW. GW levels data was collected from the Karnataka Ground Water Authority (KGWA), and GW quality data from KGWA, the Central Ground Water Board (CGWB), and Karnataka State Pollution Control Board (KSPCB), Government of Karnataka for 2013–2021. These agencies are known to regularly monitor boreholes in terms of water levels and water quality.

2.4. Precipitation data

Historical monthly precipitation data (2013 to 2022) of Kolar district was collected from Karnataka State Natural Disaster Monitoring Centre (KSNDMC) to find out the rainfall pattern in the study area. Precipitation data helped to confirm the drought conditions in the study area and helped to justify the impact of recycled water on the studied GW levels and quality.

2.5. Groundwater modelling

Measurements of GW level fluctuations in response to precipitation events can provide a practical means of estimating temporally and spatially variable GW recharge rates. Lumped unconfined aquifer models have been widely applied for studying the GW dynamics and recharge estimation in the hard rock aquifer regions of southern India (Collins et al., 2020; Subash et al., 2017; Marechal et al., 2006). Park and Parker (2008) proposed an equation for modelling GW level fluctuations in response to rainfall considering the recharge and discharge terms, however, it lacked a representation of GW pumping. Subash et al. (2017) and Kumar (2016) added the GW pumping term to the equation and developed the AMBHAS_1D model with the equation (Eq. (1)) given as:

$$\frac{dh}{dt} = -\frac{1}{Sy}\lambda h + \frac{r_f}{Sy}R - \frac{1}{Sy}D_{net} \tag{1}$$

In the above equation, h represents the hydraulic head (L), Sy is the specific yield of the aquifer system (−), λ is the discharge constant (T^{-1}), R is the rainfall (LT^{-1}), r_f is the recharge factor (−) and D_{net} is the net groundwater draft or pumping (LT^{-1}).

2.5.1. Parameter estimation

Sy and r_f are two key parameters of the model which govern the GW levels. During the calibration, the reliability of simultaneous estimation of both the parameters can be improved if enough redundancy of GW time series is considered. A sequential two-step method for estimation of Sy and r_f is adopted with a GW time series of 5 years as suggested by Sekhar et al. (2013). To separate the impact of the recycling on the parameter estimation, the period from 2013 to 2017 is selected. The ranges of specific yield and recharge factors are taken from previous studies in the hard-rock aquifer region of southern India (Goswami and Sekhar, 2022a, 2022b; Garg et al., 2020; Sekhar et al., 2013). Average net GW pumping of 150 mm/year is considered for the entire simulation period (Garg et al., 2020). The recharge factor r_f estimated in this step is averaged over the 5-year duration which is representative of a fraction of rainfall that gets converted into recharge.

2.5.2. Recharge estimation

For the estimation of recharge, Sy is kept as estimated in the previous step. Net GW pumping is kept at 150 mm/year to maintain consistency. The model estimates monthly total recharge (R_T) by minimizing the sum of the square of the error between the observed and simulated GW level from 2013 to 2021. The recharge from rainfall (R_P) is obtained by multiplying the r_f by the monthly rainfall time series. Recharge from the tank (R_L) is calculated by subtracting R_P from R_T.

2.6. Impact on land use land cover (LULC) and agricultural activities

In addition to the impacts on GW levels and quality, the present study also focuses at impacts of recycled water on land use land cover change (LULC), agricultural productivity, milk production, and fishery status specifically in the study area. A comparative analysis was carried out between the impacted area of Kolar district which receives recycled water (Narsapura village) and the non-impacted area (Nelavenki village) which is 63 km away from the impacted study area and has not received recycled water. To study the impacts required data was collected from different government organizations like LULC data from Environmental Systems Research Institute (ESRI, 2017–2022), agriculture data for the year 2021–2022 from the Department of Agriculture & Horticulture Kolar, milk production data (2021 – 2022) from Kolar district co-operative milk producer's societies union, and fishery data (2021–2022) from the Department of Fishery Sciences, Kolar to carry out this analysis.

3. Results and discussion

This section presents the analysis of the impacts of STW recycling for indirect GW recharge on the surface water quality, GW levels including GW modelling, GW quality and agricultural sectors.

3.1. Water quality analysis of secondary treated wastewater and surface tank water

Table 2 represents the water quality of the STW coming from STP and surface tank water identified for the study. The test results were compared with the NGT standards.

As the STW is pumped into the tanks, assessing the water quality in these tanks is important which represents the health of the tank. As can be seen from Table 2 the STW coming from the STP meets all the norms set by the NGT (2019) for the treated wastewater to dispose into surface water bodies or for land disposal/applications except for faecal coliform levels, which was slightly above the standard. It is known that such microbial population will reduce rapidly when water flows through multiple tanks and more so during infiltration through soil column to reach the GW (Grinshpan et al., 2021). As per NGT norms pH should range from 6.5 to 9 as most aquatic organisms prefer this as the acidic nature of water (pH < 7) enhances the proliferation of algae (Bergstrom et al., 2007; Leavitt et al., 1999). The BOD and COD predominantly represent the rapidly decomposable and more recalcitrant organic loads in the treated water and thus should not exceed 10 and 50 mg/L respectively (NGT, 2019; Zhang et al., 2018). The marginal change of COD/BOD in waters of LT and KT in spite of having undergone many days of flow, indicate that these values are stable and do not represent decomposable organics and is more likely from inorganic sources. The discharge limits for TN is <10 mg/L and PO_4- P is <1 mg/L which is meant to restrict autotrophic algal growth (leading to algal blooms), if it is in excess can sometimes lead to hypoxia at pre-dawn hours from excessive algal respiration and resultant fish death (Abu et al., 2022; Mishra et al., 2022; Yaqub et al., 2022; Alidina et al., 2014). The TSS values were lower than the discharge limit of 10 mg/L. A low TSS in the receiving waterbody indicates completeness of the treatment system.

Table 2 also presents the water quality of the first tank (LT) receiving the STW. It can be observed that the water quality in the LT has slightly improved relative to STW. The marginal improvement in water quality between the STW and its receipt at LT is suggestive of a small role of the nearly 22-h residence time for treated water to travel 53 km through pipes and its contribution to improved water quality.

As discussed earlier in Section 2.1 the STW received first at LT, remains there for a significant period before flowing 2.1 km through open channels, and passing through two more surface tanks before reaching the NT. Ideally, the NT's water quality should have improved relative to LT, due to natural treatment from flow in open channels and residence time in surface tanks. However, as shown in Table 2, it was observed that the water quality of the NT has marginally deteriorated, likely due to human activities such as fertilizer runoffs from agricultural land and fugitive discharges of domestic sewage by houses on the tank shore.

When the overflow from the NT travels to the KT by covering a distance of 16 km, while also spending a large residence time in open tanks, it can be observed that the water quality of the KT has improved relative to the NT. It is indicated that in addition to the long periods of residence time spent by STW during its flow through a cascade of surface water tanks as well as through the connecting water channels, this treated water is subjected to a long residence time within the tanks that it passes through which leads to natural treatment. The water quality of KT when compared with that of the STW, it was observed that there was almost 25 to 50 % improvement. Such an observation where the treated water encounters multiple treatment opportunities but still show small changes in quality indicates that the treatment systems are functioning to their near ideal levels and leave behind very little treatable substances. The presented results are supported by Amin et al. (2022); CGWB, (2020); Sharma and Kennedy (2017) where the water quality of treated water improved due to the self-purification mechanism in the flowing state and through dilution as an impact of GW recharge. Eslamian et al. (2018) reported the removal of dissolved organic compounds during GW recharge through SAT system as an impact of microbial biodegradation and absorption. El Arabi and Dawoud (2012) reported the removal of suspended solids, biodegradable materials, bacteria, and other microbes from treated wastewater through the vadose zone as it

Table 2
Water quality of secondary treated wastewater and surface tank water.

Sl. No.	Parameters	Unit	Hon'ble NGT discharge standards (NGT, 2019)	Sampling points			
				STW from outlet of STP	Lakshmisagara tank (LT)	Narsapura tank (NT)	Kolar Town tank (KT)
1.	pH	–	6.5–9.0	7.6	7.6	7.8	7.7
2.	BOD_5 (@20 °C)	mg/L	10	9 ± 1.0	6.2 ± 1.5	7.2 ± 2.0	6.4 ± 1.4
3.	COD	mg/L	50	48 ± 4.0	42 ± 8.0	50 + 4.0	42 ± 2.0
4.	TSS	mg/L	10	8 ± 2.2	6.8 ± 2.0	7.2 ± 2.8	6 ± 1.5
5.	NH_4 -N	mg/L	5	4.6 ± 0.8	3.7 ± 0.3	2.8 ± 0.8	2.4 ± 0.2
6.	TN	mg/L	10	7.8 ± 2.5	5.3 ± 1.4	6.9 ± 1.0	5.2 ± 0.8
7.	PO_4- P	mg/L	1.0	0.8 ± 0.3	0.3 ± 0.1	0.6 ± 0.2	0.4 ± 0.1
8.	Faecal Coliform	MPN/100 mL	< 230 allowable	280 ± 20	220 ± 16	240 ± 30	230 ± 25

Table 3
Heavy metal analysis of secondary treated wastewater and first surface tank.

Sl. No.	Metals, metalloids, and heavy metals	IS 10500 (mg/L) (BIS 10500, 2012)	Secondary treated wastewater (mg/L)	Lakshmisagara tank (LT) (mg/L)
1	Iron (Fe)	3	0.36 ± 0.02	0.26 ± 0.001
2	Manganese (Mn)	2	0.02 ± 0	BDL ± 0
3	Zinc (Zn)	5	BDL ± 0	BDL ± 0
4	Cadmium (Cd)	2	BDL ± 0	BDL ± 0
5	Lead (Pb)	0.1	BDL ± 0	BDL ± 0
6	Arsenic (As)	0.2	0.001 ± 0	0.001 ± 0
7	Chromium (Cr^{+5})	0.1	<0.1 ± 0	<0.1 ± 0
8	Nickel (Ni)	3	0.028 ± 0	0 ± 0
9	Copper (Cu)	3	0.00 ± 0	0 ± 0
10	Aluminium (Al)	0.2	BDL ± 0	0 ± 0
11	Barium (Ba)	0.7	0.045 ± 0	0.01 ± 0
12	Boron (B)	0.5	0.021 ± 0	0.001 ± 0
13	Selenium (Se)	0.01	BDL ± 0	BDL ± 0
14	Silver (Ag)	0.1	BDL ± 0	BDL ± 0
15	Mercury (Hg)	0.001	BDL ± 0	BDL ± 0
16	Molybdenum (Mo)	0.07	0.001 ± 0	BDL ± 0

Note: BDL is below the detection limit of 1×10^{-6} mg/L.

acts as a natural filter in SAT systems. Wilson et al. (1995) reported 50 % removal of nitrogen, heavy metals, and disinfection byproducts through the vadose zone.

Table 3 represents the water quality in terms of heavy metals. As can be seen from Table 2, the STW and LT's water meets even the stricter standards for drinking water (BIS 10500, 2012) for heavy metals. This suggests two possibilities: firstly, there is very low contamination of urban runoffs, and secondly, the anaerobic stages experienced by wastewaters generally cause heavy metals to precipitate and separate out, even if they are present (Manisha et al., 2023; Rao et al., 2021; Awual et al., 2020; Awual, 2019). Therefore, from this perspective, the wastewaters are rendered safe for discharge to surface water bodies. El Arabi and Dawoud, 2012 reported the removal of heavy metals and other inorganic contaminants from wastewater during GW recharge as an impact of geochemical reactions such as mineral precipitation, dissolution, adsorption, and redox reactions.

Detailed studies on the presence of emerging contaminants in STW and surface water in the study area are underway. Preliminary results presented in Table 4 indicate their absence in STW and subsequently in the first surface tank (LT) receiving STW. This is because the STW undergoes different levels of natural treatment as it experiences a long residence time (>14 days) in tanks (Manisha et al., 2023; Teo et al., 2022; Icekson-Tal et al., 2003).

The rejuvenated tanks are home to a variety of birds, such as fish eagles, herons, and various types of ducks, indicating the presence of a large fish population, which serves as their primary food source. Large and smaller fish were also observed in these tanks, starting from the LT, indicating successful breeding. These observations suggest that the recharged water quality is suitable for aquatic life and supports fish growth and reproduction, which was previously a concern when selecting fish for commercial cultivation in these tanks. In the past, it was challenging for fish to breed in what was perceived as "hard/polluted" water. However, these observations demonstrate that the approach of recharging water in the tanks allows for successful fish breeding and growth, eliminating the need for separate breeding programs and seeding with fingerlings. These observations, showing fish in various stages of breeding and growth, clearly indicate the suitability of this approach not only for fish cultivation but also for their breeding and the long-term sustainability of surface tank water.

Table 4
Summary of emerging contaminants in secondary treated wastewater and surface tank.

Sl. No.	Test parameter	Type	Secondary treated wastewater (mg/L)	Lakshmisagara tank (LT) (mg/L)
1	Fluoroquinolones	Antibiotics	BDL	BDL
2	Ciprofloxacin		BDL	BDL
3	Azithromycin		BDL	BDL
4	Tetracycline		BDL	BDL
5	Norfloxacin		BDL	BDL
6	Acetaminophen	Pain killers	BDL	BDL
7	Ibuprofen		BDL	BDL
8	Diclofenac		BDL	BDL
9	Sulfamethoxazole		BDL	BDL
10	Cetirizine		BDL	BDL
11	Xylenol	Pharmaceutical and personal care products	BDL	BDL
12	Triclosan		BDL	BDL

Note: BDL is Below detection limit (< 0.001)].

3.2. Impact on groundwater levels

Fig. 3 (a) and (b) represents the historical data for GW levels and precipitation of impacted as well as non-impacted boreholes of Kolar district.

It can be observed from Fig. 3 that the GW levels before recycling STW (March 2018) were around 18 mbgl (meters below ground level) which improved to 7.5 mbgl for NB and for KB it was 33 mbgl in Aug 2018 which rose to 9 mbgl in September 2018. A clear immediate positive impact on GW levels can be observed as the levels increased by 58 % and 73 % respectively in the studied impacted boreholes. Literature reports a linear relationship between GW recharge and rainfall (Rasel et al., 2023; Anuraga et al., 2006) but it can be observed from the historical precipitation data (KSNDMC, 2020) represented in Fig. 3 that 2018–2019 was a rain deficit period but still the GW levels increased which confirms direct impact of recycled water (STW) filled in the existing surface tanks near to the studied boreholes. This clearly has resulted because surface water from rejuvenated tanks has infiltered through soil layers and percolated vertically downward deep in the soil through the unsaturated zone towards the water table. The movement of water also depends on soil permeability or hydraulic conductivity. Pore space in the soil serves as the storage compartment for water. It is reported that the Karnataka state is underlain by peninsular gneisses, and granites (Ramaiah et al., 2017). The studied surface tanks are also located at such highly fractured and weathered rock and have a sufficient thickness of permeable vadose zone which helps for speedy GW recharge (Veeranna and Jeet, 2020; DEIAA, 2019; Asano and Cotruvo, 2004). Fig. C (a) (Appendix C) represents maps showing low water levels in Kolar district before commencement of the recycling and Fig. C (b) represents increased water levels after commencement of the project.

As discussed in Section 2.1 soil type in Kolar district ranges from red loamy soil to red sandy lateritic soil which is also characterized by low water holding capacity and increased hydraulic conductivity (GoK, 2016; Sivapullaiah et al., 2003). This soil has an infiltration rate of >10 in. per hour (CGWB, 2020) thus an immediate response can be seen in the impacted boreholes which were in the nearby vicinity of the rejuvenated surface tanks. Thus, it can be concluded that indirect artificial recharge of the GW has a significant role in the development and management of drought-prone semi-arid areas as it boosts the GW level. Nandan et al. (2021); Shawaqfah et al. (2021); Dillon and Arshad (2016); El Arabi and Dawoud (2012); and Icekson-Tal et al. (2003) also reported improved GW levels through indirect GW recharge methods.

Fig. 3 (c) and (d) represents water levels of two boreholes (SB and HB) with delayed impact where it can be observed that in both the boreholes there is no immediate improvement in the GW levels post recycling. It is thus concluded that treated water has not reached to these areas which are far away (at a distance of 10 to 14 km from the KT) until 2020. Whereas it can also be observed that the water levels have increased in both SB and HB after 2020. At SB, the water level increased by 80 % from October 2021 to November 2021 whereas at HB it increased by 48 % from October 2020 to November 2020. This is attributed to the fact that these two boreholes have shown a delayed impact with respect to 2018 post recycling and may be attributed to lateral movement of percolated underground water

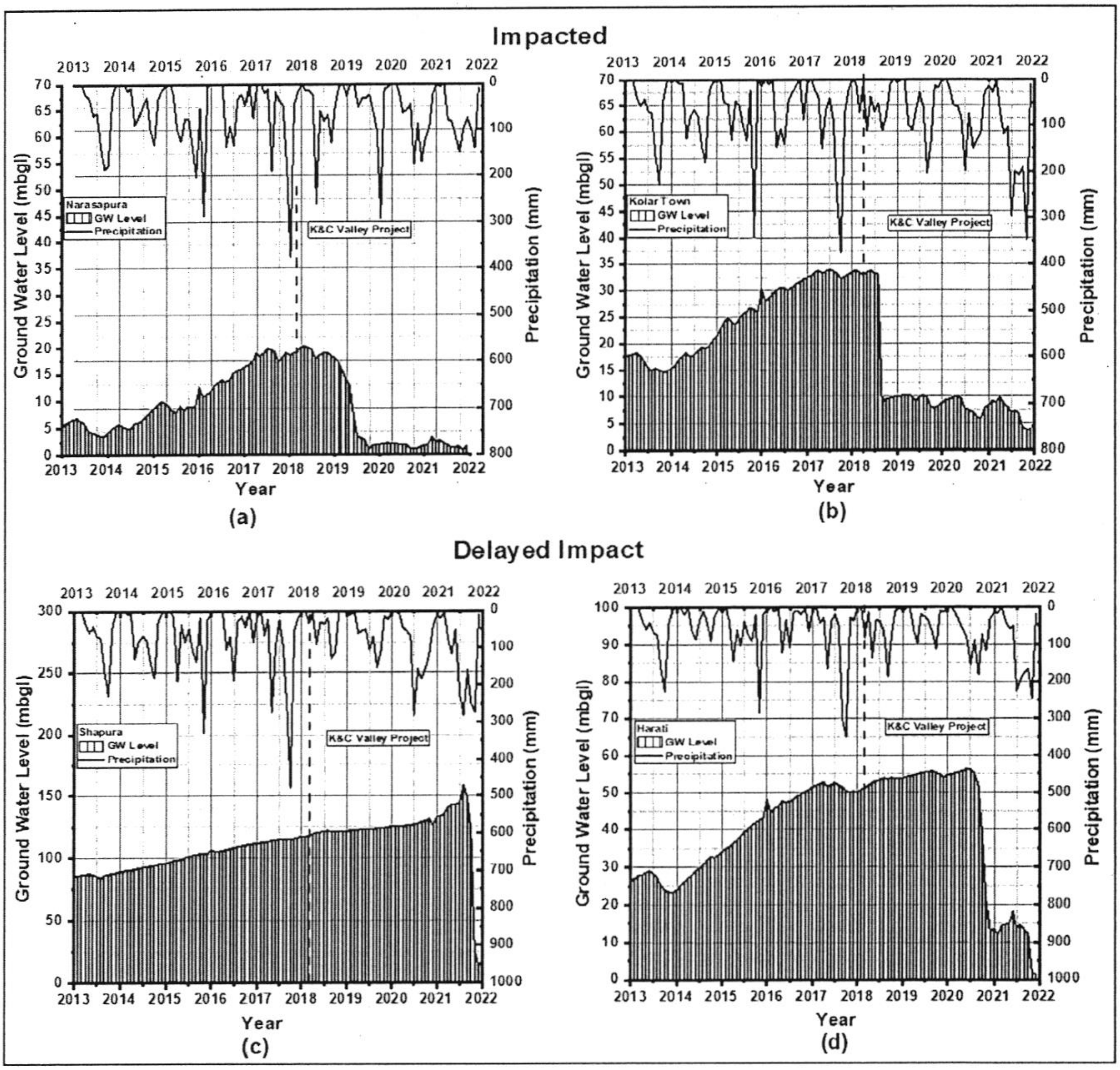

Fig. 3. Change in groundwater levels between before and after recycling of secondary treated wastewater for impacted boreholes (a and b) and non-impacted boreholes (c and d) Source: Precipitation data from KSNDMC and GW water level from KGWA and CGWB.

over a long period. To order to confirm these findings GW modelling was carried out.

3.3. Groundwater modelling

As discussed in Section 2.5 a physically lumped unconfined model AMBHAS_1D was used to model the GW level fluctuation in two steps considering the GW recharge, discharge, and pumping. In the first step model calibration was carried out for a period of 5 years from 2013 to 2017 during which the GW levels were representative of long-term GW balance in the non-impacted region. The estimated set of parameters along with performance indices "Root Mean Squared Error" (RMSE) and "Coefficient of determination" (R^2) are listed in Table 5. Fig. 4 represents the comparison of simulated and observed GW levels for the calibration period. In the second step, the calibrated set of aquifer parameters were forced into the model to estimate the monthly recharge values corresponding to the best fit between observed and simulated GW levels from 2013 to 2021.

Fig. 5 represents the estimated monthly recharge and the simulated GW level time series for 2013–2021. The monthly recharge estimates are validated by comparing the model simulated GW levels with observed GW tanks in terms of R^2 and RMSE (Goswami and Sekhar, 2022a, 2022b; Sekhar et al., 2013. In Fig. 5, blue and green bars correspond to the recharge from rainfall and tanks respectively. As discussed in Section 3.2 the two impacted boreholes reflect good GW recovery just after recycling was started in March 2018. The other two boreholes SB and HB, showed a delayed GW

Table 5
Estimated parameters and performance of the model calibration.

Sl.No.	Boreholes	RMSE (m)	R^2	rf	Sy
1	Narsapura (NB)	2.8	0.7	0.127	0.05
2	Kolar (KB)	3.22	0.77	0.094	0.039
3	Shapur (SB)	3.61	0.88	0.124	0.018
4	Harati (HB)	3.97	0.85	0.099	0.025

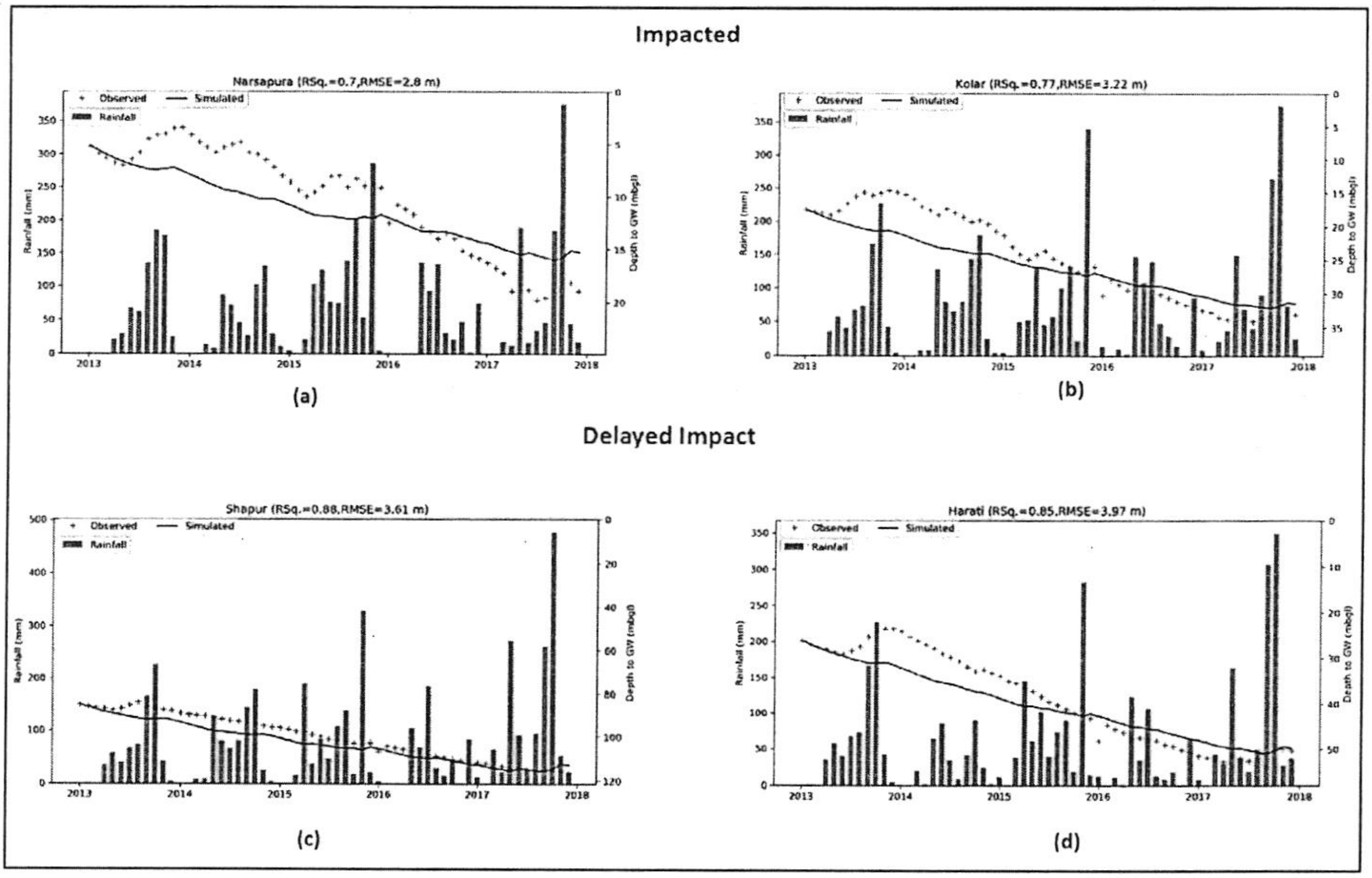

Fig. 4. Comparison of simulated and observed GW levels for calibration period (2013–2017).
Source: Precipitation data from KSNDMC and GW levels data from KGWA and CGWB.

recovery because of slow lateral movement of GW as these locations are far from the rejuvenated tanks. The annual water budget for each location is tabulated and provided in Table 6. Daily recharge rate before 2018 are in the range of 0.1 to 0.48 mm for all four boreholes studied. The daily recharge rates of NB and KB reflect the impact of recycling stating from year 2018 as the daily recharge rate is almost 2–10 times higher for 2018 and 2019. The sharp rise in the observed GW levels at impacted locations in range of 20 m to >100 m within 4–6 months duration supports the higher recharge estimates because of contribution of rejuvenated tanks. Since 2019, these two borehole sites exhibit low seasonal GW level variability (around 5 m) as these sites are in the vicinity of the tanks which act as constant head boundary condition. The other two boreholes (SB and HB), experience 5–10 times rise in daily recharge rate in 2020 and 2021 respectively confirming a delayed impact with respect to 2018. Net pumping to recharge ratio at all locations before the recycling was >1 signifying unsustainable GW pumping in the region. The daily recharge rate improved significantly post 2018 because of the extra recharge from the tanks which is much higher than the direct recharge from rainfall. The increased recharge compensates for pumping and the ratio of net pumping to total recharge drop below 1. The GW recharge estimates based on GW modelling indicate that this large scale recycling of STW has enhanced the GW recharge in the region resulting in rapid recovery of GW storage (Manisha et al., 2023; El Arabi and Dawoud, 2012; Icekson-Tal et al., 2003).

3.4. Impact on groundwater quality

Results represented in Section 3.3 confirm that STW filled in the tanks has recharged the GW table of the study area and thus this section represents its impact on GW quality as represented in Figs. 6, 7, 8 and 9.

The graphs in Figs. 6-9 illustrate that, the groundwater quality in the impacted boreholes has improved across all studied parameters when comparing the data from before and after the recycling period. Observations indicate that in the case of NB, there was no significant change in pH value. However, a notable reduction in water quality parameters was observed, including a 55 % reduction in hardness, 23 % reduction in TDS, 12 % reduction in EC, 46 % reduction in Ca+, 62 % reduction in Na^+, 22 % reduction in Cl^-, and 84 % reduction in NO_3^-. Similarly, for KB, no change in pH value was observed, but there was a significant reduction in water quality parameters, including a 70 % reduction in hardness, 76 % reduction in TDS, 85 % reduction in EC, 88 % reduction in Ca^+, 88 % reduction in Na^+, 96 % reduction in Cl^-, and 93 % reduction in $NO3^-$. Fig. D1 and D2 (Appendix D) represents reduction in Mg^+, K^+, SO_4^{2-}, and F^- when compared between before and after recycling period. Clearly the hard waters of deep aquifers (before recycling) with a lot more dissolved salts have transformed into a more agriculture friendly water (Hasan et al., 2023; Teo et al., 2022).

Figs. 6, 7, 8, and 9 highlight the dilution effect on the water quality parameters resulting from the recharge of recycled water into the deep aquifer during its infiltration through the soil. As discussed earlier, the STW held in tanks infiltrates into the subsurface and deeper aquifers rapidly, and percolates vertically through the unsaturated zone towards the water table (Saleem et al., 2016; Bekele et al., 2011). This infiltration process through the soil is slow, which results in the purification of any residual chemicals that may have escaped the wastewater treatment process. Moreover, this filtration process occurring over months starves the potential pathogens, ensuring their rapid die-off (Hasan et al., 2023; Hasan et al., 2021; Maurya et al., 2020; Islam et al., 2020).

The removal mechanisms involved in the recycling process include physical filtration, biodegradation, adsorption, chemical precipitation, ion

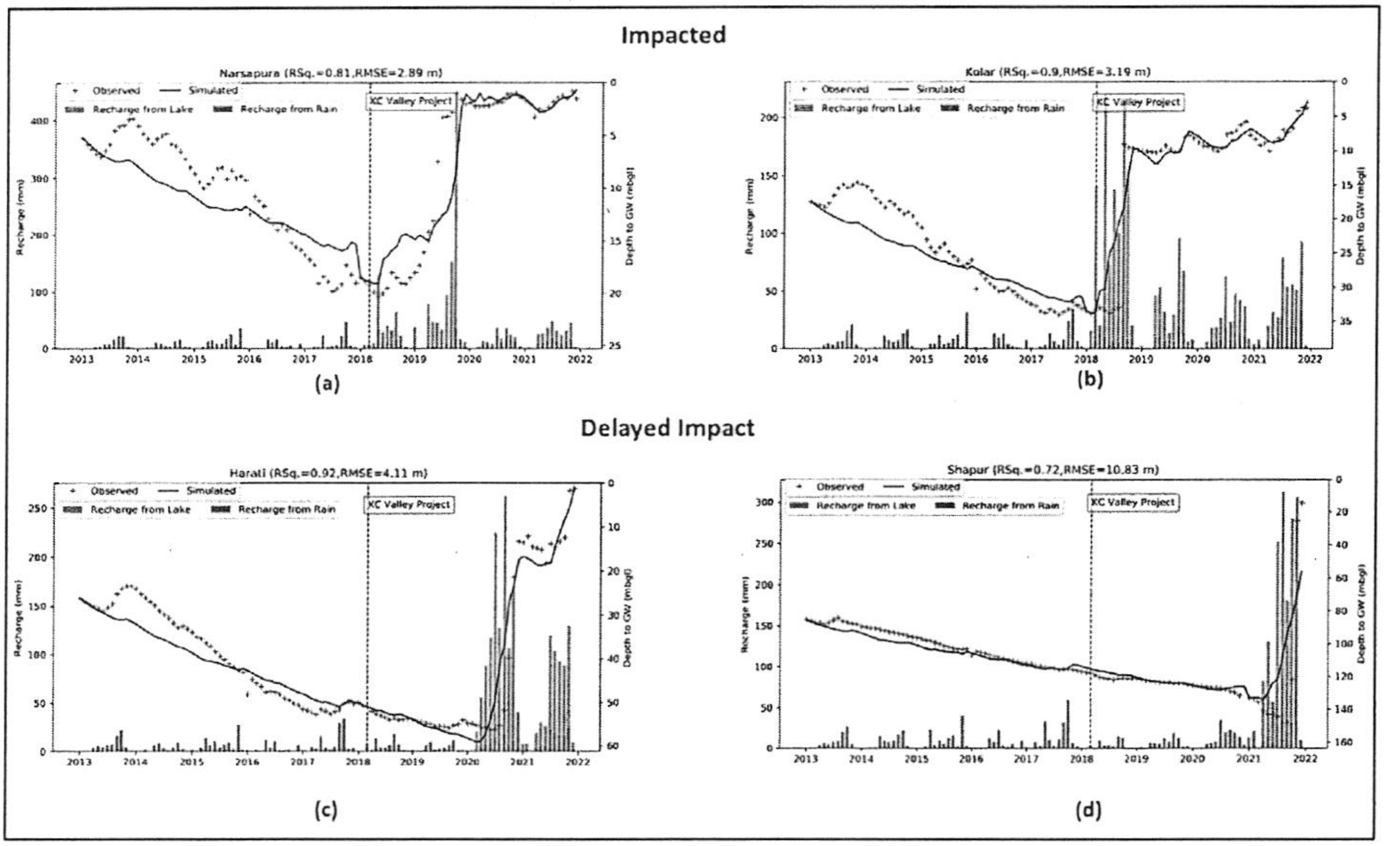

Fig. 5. Estimated monthly recharge from rainfall and tanks
Source: Precipitation data from KSNDMC and GW levels from KGWA and CGWB.

exchange, and dilution. Microbial action typically converts organic contaminants into simpler compounds, while filtration through various soil layers removes suspended matter and pathogens (Islam et al., 2021; Mazrouaa et al., 2019; Bekele et al., 2011), confirming the safety of the recharged groundwater for reuse. As shown in Fig. 6-9, the delayed impact of recycled water on groundwater recharge in SB and HB resulted in no significant impact on water quality before 2019, but a significant improvement was observed in 2020–2021 due to dilution. The results of this study are consistent with the findings of Zhang et al. (2018), who reported improved groundwater quality with a standard of class 1 WQ Index in a laboratory experimental setup using reclaimed water for groundwater recharge. El Arabi and Dawoud (2012) observed the removal of suspended solids, biodegradable substances, nitrogen, phosphorus, and heavy metals due to the vadose zone acting as a natural filter. Bekele et al. (2011) reported 66 % removal efficiency for fluoride (F^-), 62 % for iron (Fe), 51 % for total organic carbon (TOC), and 30 % for phosphorus (P) through a MAR system when treated

Table 6
Annual water budget and contribution of recharge from rain and tanks.

Boreholes	Year	2013	2014	2015	2016	2017	2018	2019	2020	2021
	Net pumping (mm)	150	150	150	150	150	150	150	150	150
Narsapura	Total recharge (mm)	90	67	139	69	120	352	966	181	284
	Recharge from rain (mm)	90	67	139	69	120	89	80	109	109
	Recharge from lake (mm)	0	0	0	0	0	263	886	73	175
	Daily recharge rate (mm/day)	0.25	0.18	0.38	0.19	0.33	0.97	2.65	0.50	0.78
	Net pumping to total recharge ratio	1.6	2.2	1.0	2.1	1.2	0.4	0.1	0.8	0.5
Kolar	Total recharge (mm)	67	68	88	56	108	1101	358	293	429
	Recharge from rain (mm)	67	68	88	56	108	53	71	87	150
	Recharge from lake (mm)	0	0	0	0	0	1048	287	206	279
	Daily recharge rate (mm/day)	0.18	0.19	0.24	0.15	0.30	3.02	0.98	0.80	1.18
	Net pumping to total recharge ratio	2.2	2.2	1.7	2.6	1.3	0.1	0.4	0.5	0.3
Shapur	Total recharge (mm)	89	90	123	66	173	56	81	138	1647
	Recharge from rain (mm)	89	90	123	66	173	56	81	138	184
	Recharge from lake (mm)	0	0	0	0	0	0	0	0	1463
	Daily recharge rate (mm/day)	0.24	0.25	0.34	0.18	0.48	0.15	0.22	0.38	4.51
	Net pumping to total recharge ratio	1.6	1.6	1.2	2.2	0.8	2.6	1.8	1.0	0.0
Harati	Total recharge (mm)	71	37	87	39	106	65	47	1217	640
	Recharge from rain (mm)	71	37	87	39	106	64	45	84	119
	Recharge from lake (mm)	0	0	0	0	0	1	2	1134	520
	Daily recharge rate (mm/day)	0.19	0.10	0.24	0.11	0.29	0.18	0.13	3.33	1.75
	Net pumping to total recharge ratio	2.1	4.0	1.7	3.8	1.4	2.3	3.1	0.1	0.2

Source: Precipitation data from KSNDMC and GW level from KGWA and CGWB.

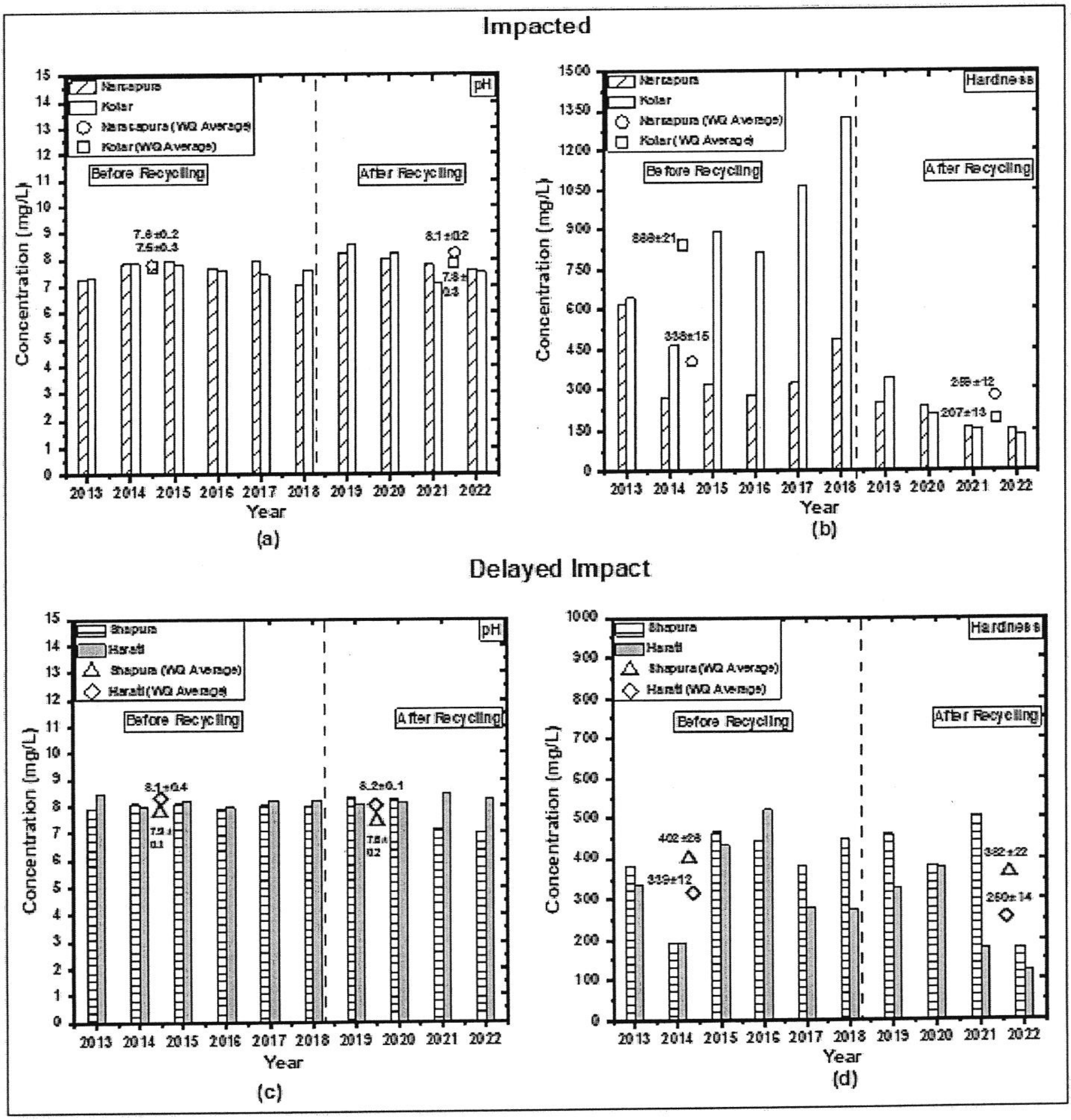

Fig. 6. Impact on groundwater quality (physio-chemical)
Source: KGWA and CGWB
Note: Before recycling period is 2013–2017 whereas after recycling period is 2018–2022.

wastewater was used for groundwater recharge. Icekson-Tal et al. (2003) reported 70 % removal efficiency for COD, BOD, and other substances through a SAT system when treated wastewater was used for groundwater recharge. Experimental studies by Bauwer, 1991 also reported reduced levels of N, TOC, sulfate, and faecal coliforms in recharged groundwater.

3.5. Impact on LULC, agriculture, milk, and fish production

Fig. 10 represents the topographic view of the impacts of using STW for indirect GW recharge on land use and land cover of impacted area. Land Use Land Cover (LULC) maps provide information to understand the current landscape (Manisha et al., 2023; Rasel et al., 2023). Annual LULC information on national spatial databases enables the monitoring of temporal dynamics of the study area where land cover is the physical material at the surface of the earth and land use is the description of utilizing the land for socio-economic activities. A significant shift in LULC was observed between 2017 and 2022 where the number of water bodies have increased by 5 times, the trees by 43 %, flooded vegetation by 67 times, cropping land by 4.2 %, built area by 43 %, whereas bare ground and rangeland decreased by 44 % and 30 % respectively which gives a clear indication of the

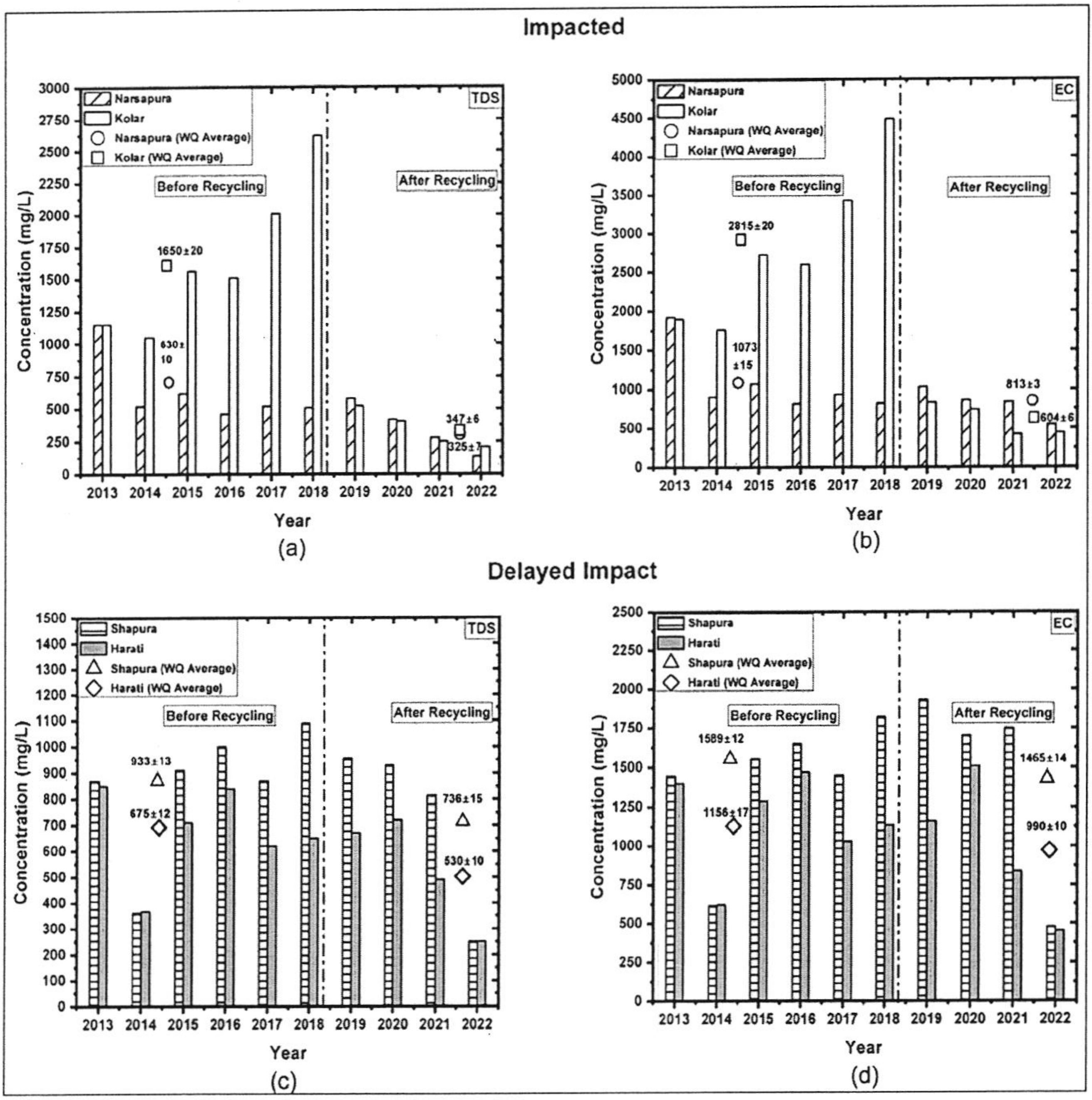

Fig. 7. Impact on groundwater quality (physical parameters)
Source: KGWA and CGWB
Note: Before recycling period is 2013–2017 whereas after recycling period is 2018–2022.

increased availability of water and brought about positive impact of K&C valley water on the LULC.

Fig. 11 (a) and (b) presents the cultivated area that is utilized for different types of crop production. It can be observed that the area utilized for crop production is more in the impacted area (Narsapura village) when compared to the non-impacted area (Nelavenki village). Significant improvement is observed in area cultivated using vegetables (80 %), cereals (35 %), plantations (38 %), flowers (100 %), fruits (57 %), and pulses (40 %). This is due to the increased access to GW which is possible to the improved GW table by K&C valley water. Similarly, significant changes in crop productivity (Fig. 10 b) are observed for vegetables (37 %), fruits (2 %), plants (13 %), cereals (11 %), and pulses (12 %). Overall, there is a positive trend in cropped area (agriculture) through the availability of indirect GW recharge which has "greened" the otherwise semi-arid and nearly desertified area. It can be attributed that previously in the study area the drought conditions have resulted in water scarcity, low in situ soil moisture and soil erosion, poor crop and livestock productivity, poor soil conditions with low organic C, nutrients such as phosphorous and zinc which are now taken care due to secure water availability. It can also be concluded that the assured availability of irrigation water throughout the year (Manisha et al., 2023; Ofori et al., 2021) and the revival of the GW table has shifted the cropping pattern from low water requiring crops (e.g., pulses, oil seed) to high water requiring and also water-intensive /water sensitive crops (vegetables, flowers, etc.).

Fig. 11 (c) and (d) represent the impact on milk and fish production in the impacted area. It can be observed (Fig. 11 c) that the quantity of milk production has improved by 33 % in the impacted area when compared with the non-impacted area due the higher observed increase in the

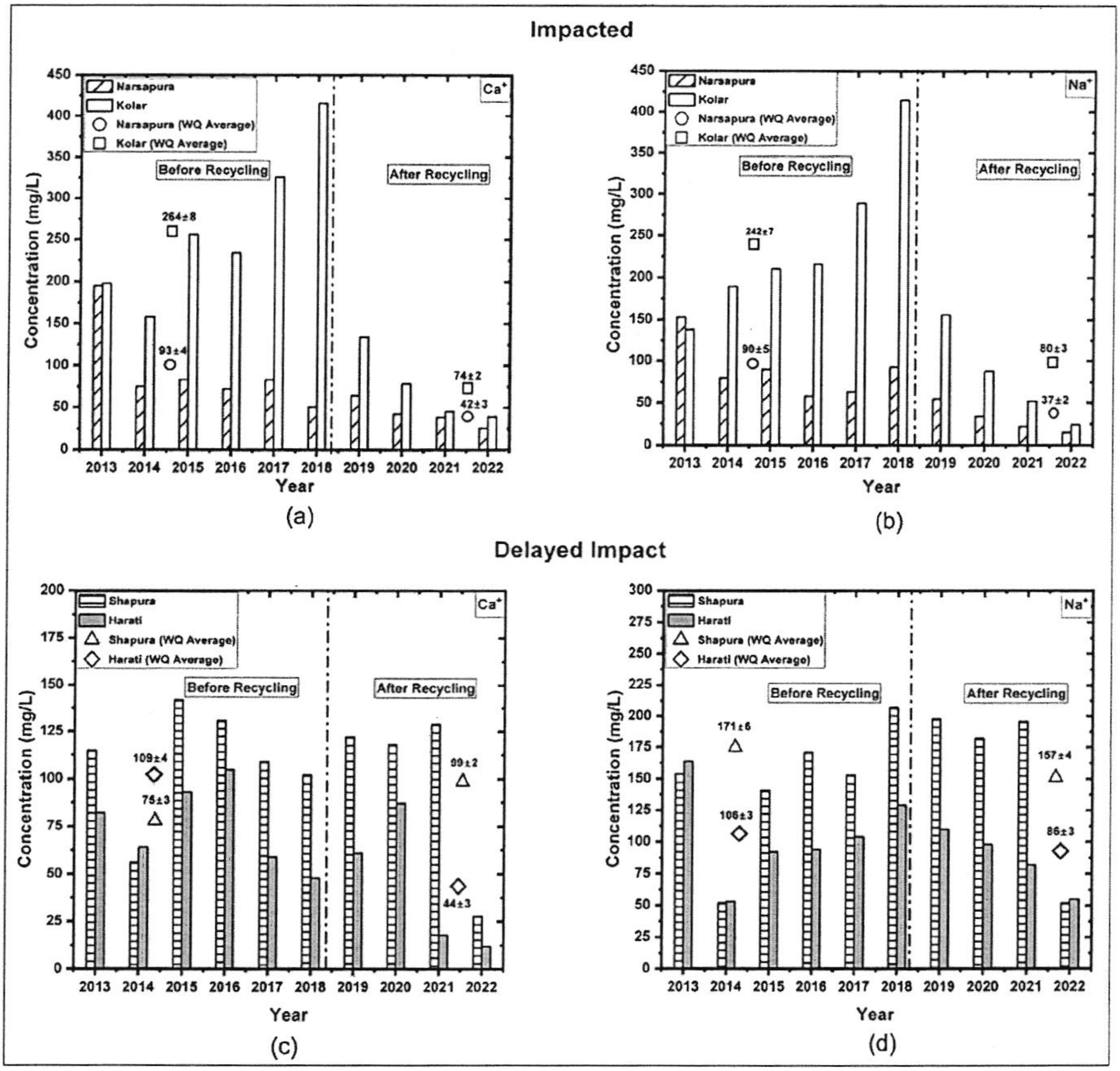

Fig. 8. Impact on groundwater quality (Cations)
Source: KGWA and CGWB
Note: Before recycling period is 2013–2017 whereas after recycling period is 2018–2022.

availability of green fodder for the animals and is also a key determinant for maintenance and viability of maintaining milch cattle (Manisha et al., 2023; Zaibel et al., 2019). It thus appears that the improved availability /reliability of water for fodder cultivation has a positive impact on livestock rearing along with milk production (although the extent of land dedicated to fodder and their yields are not reported here).

Fig. 11 (d) represents the impact of using STW in tank rejuvenation on fish production levels. During the drought conditions the fish production decreased as a result of lower water availability and perhaps a shorter growth period for the introduced fish when most of the tanks dried up rapidly. However, due to the implementation of the large scale recycling, there is year-round availability of water in the tank and the tanks are generally filled to maximum levels. It is suggested that owing to the higher reliability of the water in the tanks as well as the higher volumes of water currently stored in these tanks, the fish productivity has resulted in an increase by 341 % when compared with the non-impacted area. As mentioned earlier, there is a significant improvement in water quality, especially the hardness, because of which there is now an opportunity to raise not only larger numbers of fish but also a greater variety while also facilitating their breeding in situ.

Studies supporting the presented results (Zaibel et al., 2019), namely the assessment of the food web starting from phyto-plankton and zooplanktons, indicate that the aquatic flora (phytoplankton) and fauna (zooplankton) required to support good fish populations are present in adequate numbers in the tank water (STW). The increased availability of plankton, required nutrients such as ammonia, nitrite, nitrate, calcium, and potassium have now clearly improved and is supported by the food web analysis (not presented in this paper). Similarly, such additional nutrients are generally used for fertilization of fish ponds in aquaculture which is also a known practice around the World (Zaibel and Zilberg, 2021). Nandan et al. (2021);

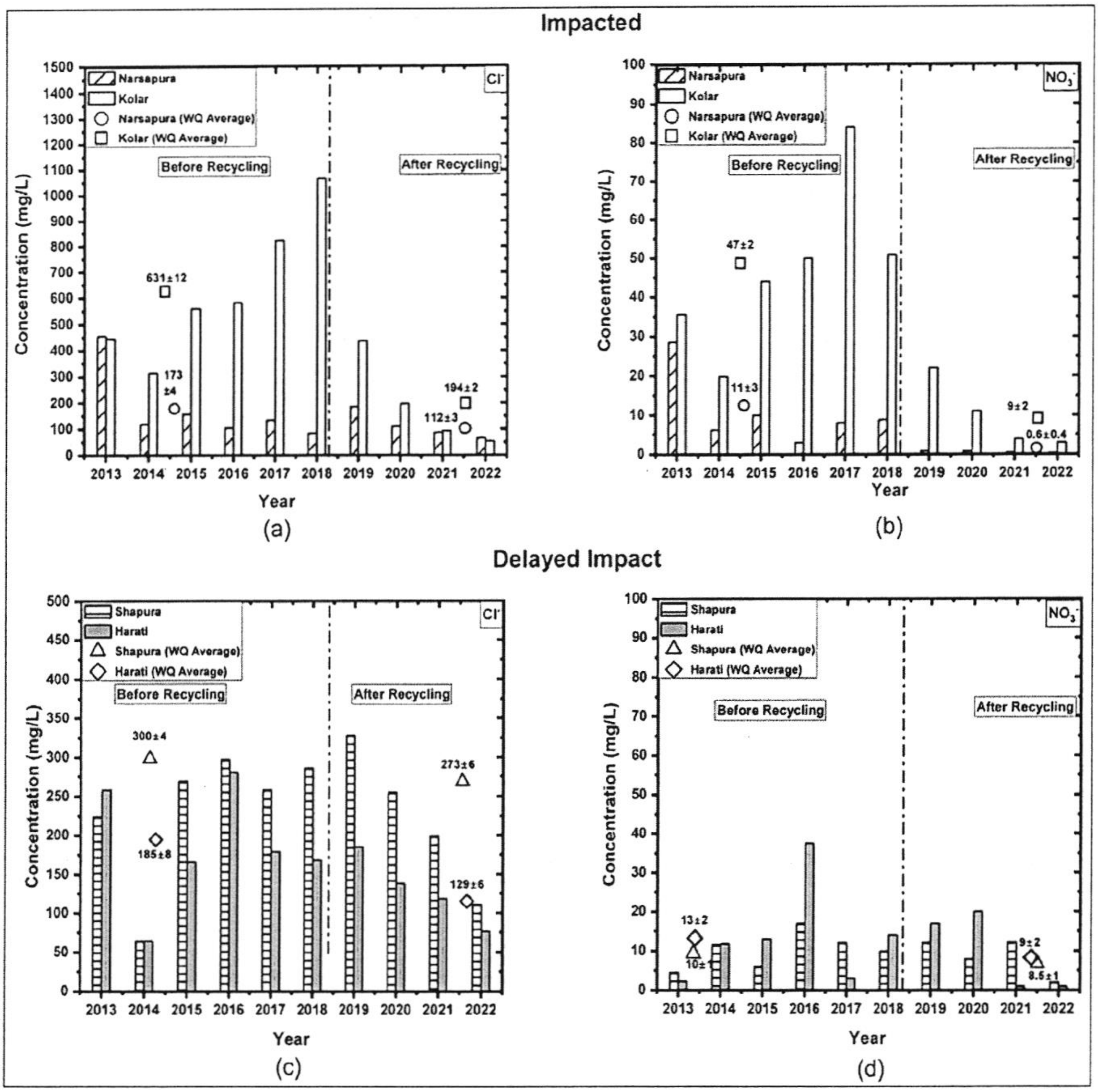

Fig. 9. Impact on groundwater quality (Anions)
Source: KGWA and CGWB
Note: Before recycling period is 2013–2017 whereas after recycling period is 2018–2022.

Pedrero et al. (2010) supports the results of the presented study and reported positive impact on GW, agricultural sector, and socio-economic conditions in water-scarce regions through managed aquifer recharge (MAR).

4. Conclusions

In conclusion, this study highlights the success of large-scale recycling of secondary treated wastewater in addressing freshwater scarcity in water-stressed regions, particularly the semi-arid Kolar district. The large scale recycling of secondary treated wastewater effectively rejuvenated existing surface tanks and recharged groundwater in neighbouring villages of Bangalore city. The AMBHAS_1D model was utilized to quantify the groundwater recharge rates in hard rock aquifers with fractured gneiss, granites, schists, and highly fractured weathered rocks, and the results demonstrated recharge rates up to 3 mm/day, which is 10 times the otherwise recharge rates. This study also quantifies the positive impacts of this recycling effort on groundwater levels and quality. Due to additional recharge coming from the recycling of secondary treated wastewater, the groundwater levels increased by 58 to 73 %. Also, due to infiltration through the tank soil and strata, the groundwater hardness improved by 50–70 %. Furthermore, the land use and land cover studies confirmed a fivefold increase in water bodies, resulting in a significant reduction in background and rangeland, increased agricultural activities, increased milk production and increased fish production.

These findings provide valuable insights for stakeholders to accelerate plans for reusing treated wastewater for indirect groundwater recharge and conserving freshwater. Large-scale water recycling schemes, such as the K&C valley project, can be replicated in towns and cities facing drought

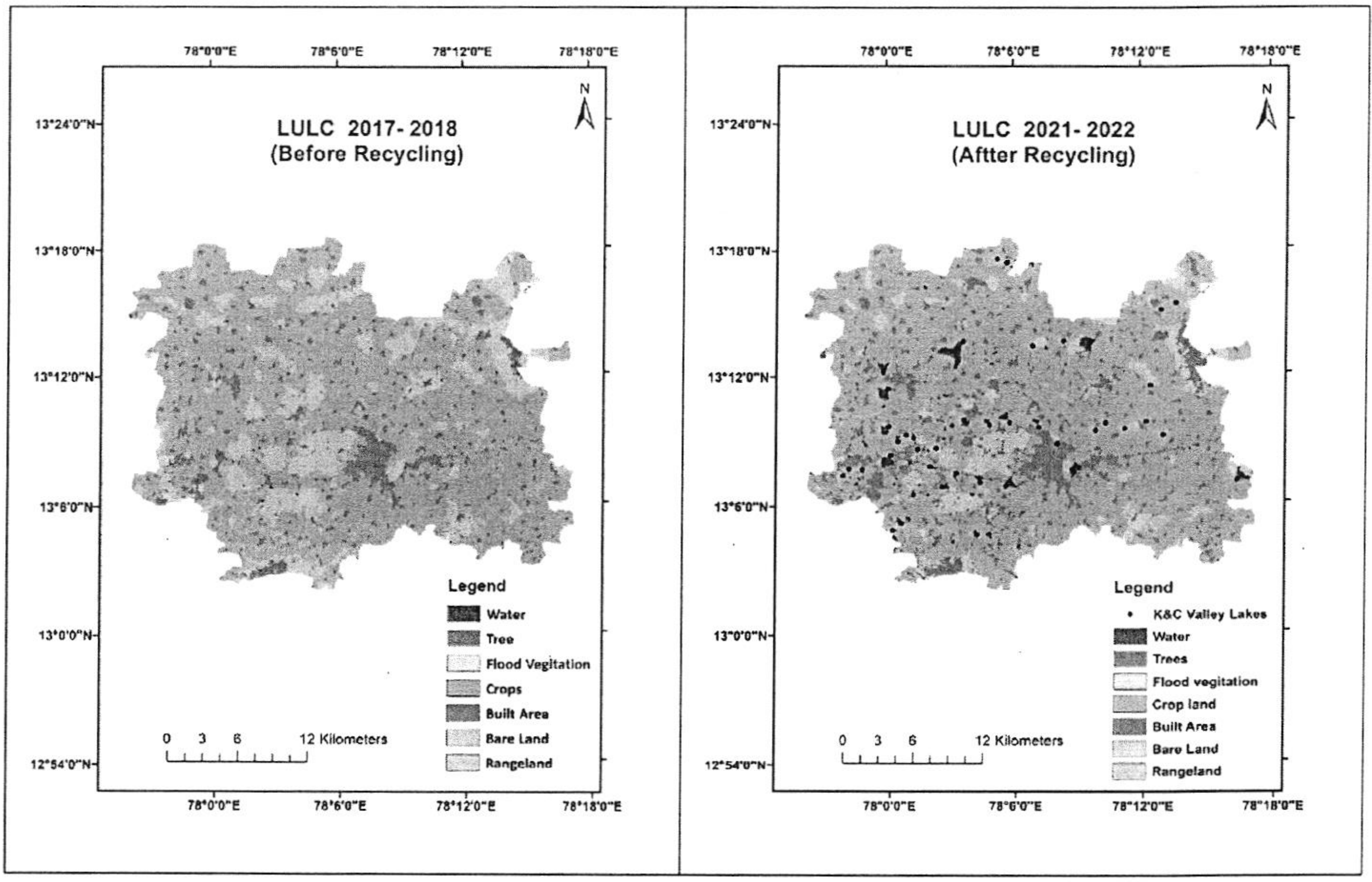

Fig. 10. Impact on LULC (2017–2018 to 2021–2022)
Source: ESRI (2017 to 2022).

situations, providing long-term water security. However, it is crucial to monitor groundwater quality regularly and investigate the long-term impacts of using secondary treated wastewater for indirect groundwater recharge. By doing so, we can continue to address freshwater scarcity sustainably while supporting agricultural and economic growth in water-stressed regions.

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CRediT authorship contribution statement

Kavita Verma – Corresponding Author, study design, data collection, analysis, and drafting of the manuscript.

Manjari Manisha –Study on Socio-economic aspects, data collection, analysis, and drafting of the manuscript.

Santrupt RM- Data collection and analysis, and plotting graphs.

Anirudha TP- Data collection and analysis, and plotting graphs.

Shubham Goswami- Groundwater Modelling and Analysis.

M. Sekhar- Conception, Groundwater Modelling, and review of the article.

Ramesh N- Data collection from different organizations for the socio-economic study.

Mohan Kumar MS- Conception, designing of the study, and review of the article.

Chanakya HN- Conception, designing of the study, and review of the article.

Lakshminarayana Rao- Conception, designing of the study, and review of the article.

Note: Santrupt RM and Anirudha TP have an equal contribution.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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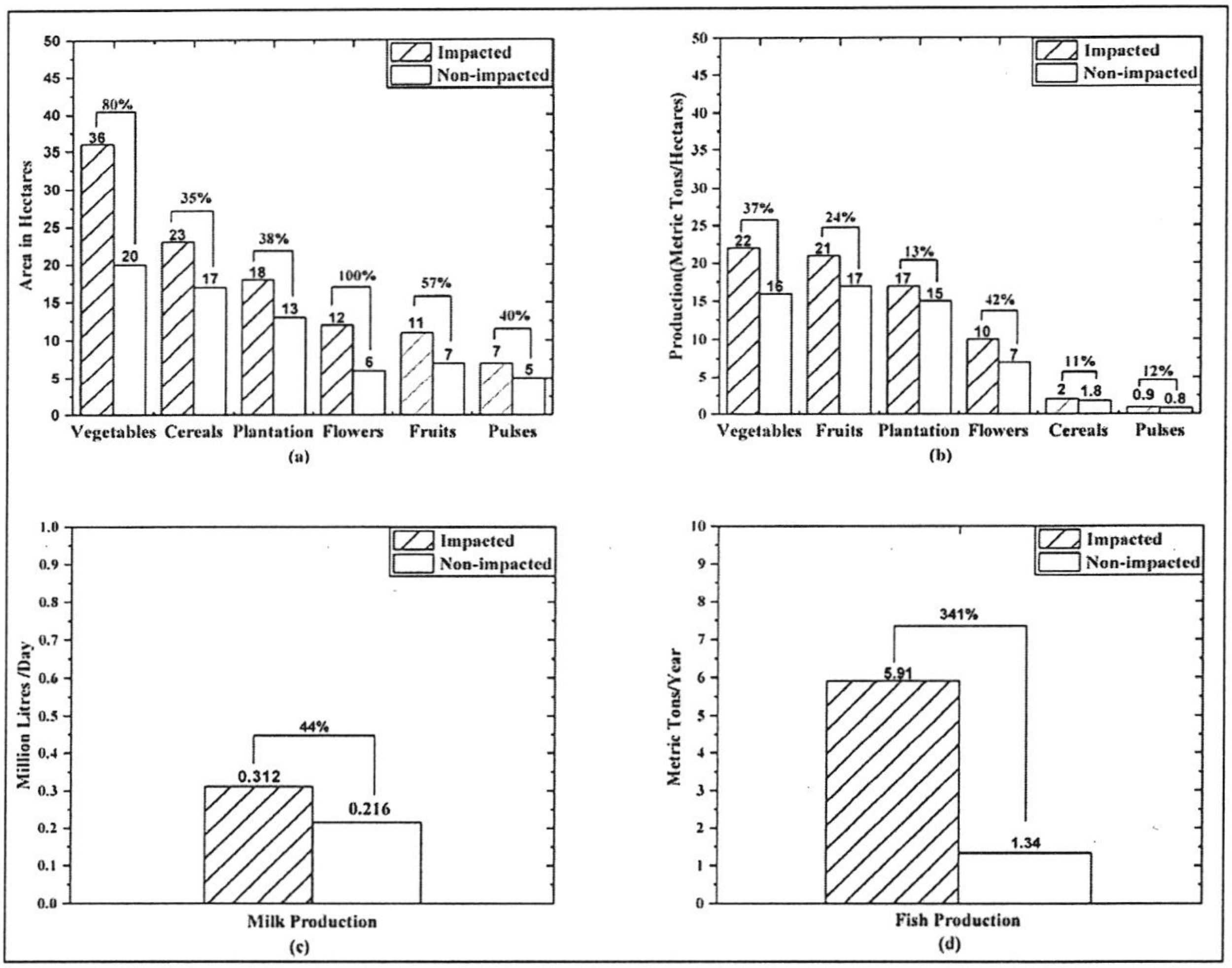

Fig. 11. (a) and (b) Impact on crop productivity, (c) milk and (d) fish production for 2021–2022
Source: Department of Agriculture & Horticulture Kolar, milk production data (2021–2022) from Kolar-Chikkaballapur district co-operative milk producer's societies union ltd. Kolar, and fishery data (2021–2022) Department of Fishery Sciences, 2021, Kolar.
Note: Plantations represent cultivation of- cashew, silver oak, eucalyptus, coconut, areca nut, tamarind, and mulberry; Vegetables- tomato, potato, beans, cabbage, green chili, capsicum, carrot, etc.; Fruits- mango, banana, sapota, guava, grapes, watermelon, pomegranates, papaya, etc.; Cereals- ragi, paddy, maize, jowar, minor millets, etc.; Flower- marigold, chrysanthemum, jasmine, rose, crossandra, etc.; Pulses-red gram, field bean, toor, cowpea, horse gram, green gram, etc. Oil seed – ground nut, sunflower.

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References

Abu, A., Carrey, R., Valhondo, C., Domenech, C., Soler, A., Martinez-Landa, L., Diaz-Cruz, S., Carrera, J., Otero, N., 2022. Pathways and efficiency of nitrogen attenuation in wastewater effluent through soil aquifer treatment. J. Environ. Manag. 321, 115927.

Alam, S., Borthakur, A., Ravi, S., Gebremichael, M., Mohanty, S.K., 2021. Managed aquifer recharge implementation criteria to achieve water sustainability. Sci. Total Environ. 768, 144992.

Alidina, M., Li, D., Ouf, M., Drewes, J.E., 2014. Role of primary substrate composition and concentration on attenuation of trace organic chemicals in managed aquifer recharge systems. J. Environ. Manag. 144, 58–66.

Amin, H.M., Gad, A., El-Rawy, Mustafa, Abdelghany, U.A., Sadeek, R.A., 2022. Improvement of partially treated wastewater quality by soil aquifer treatment in upper Egypt. Journal of Engineering Science and Technology 17 (1), 0689–0712.

Anuraga, T.S., Ruiz, L., Kumar, M.M., Sekhar, M., Leijnse, A., 2006. Estimating groundwater recharge using land use and soil data: a case study in South India. Agric. Water Manag. 84 (1–2), 65–76.

APHA, 2005. Standard Methods for the Examination of Water and Wastewater. 21st edition. American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC.

Asano, T., Cotruvo, J.A., 2004. Groundwater recharge with reclaimed municipal wastewater: health and regulatory considerations. Water Res. 38 (8), 1941–1951.

Awual, M.R., 2016. Assessing of lead (III) capturing from contaminated wastewater using ligand doped conjugate adsorbent. Chem. Eng. J. 289, 65–73.

Awual, M.R., 2019. A facile composite material for enhanced cadmium (II) ion capturing from wastewater. J. Environ. Chem. Eng. 7 (5), 103378.

Awual, M.R., Hasan, M.M., 2015. Fine-tuning mesoporous adsorbent for simultaneous ultra-trace palladium (II) detection, separation and recovery. J. Ind. Eng. Chem. 21, 507–515.

Awual, M.R., Hasan, M.M., Islam, A., Asiri, A.M., Rahman, M.M., 2020. Optimization of an innovative composited material for effective monitoring and removal of cobalt (II) from wastewater. J. Mol. Liq. 298, 112035.

Barry, K.E., Vanderzalm, J.L., Miotlinski, K., Dillon, P.J., 2017. Assessing the impact of recycled water quality and clogging on infiltration rates at a pioneering soil aquifer treatment (SAT) site in Alice Springs, Northern Territory (NT), Australia. Water 9 (3), 179.

Bauwer, H., 1991. Groundwater recharge with sewage effluent. Water Sci. Technol. 23 (10–12), 2099–2108.

Bekele, E., Toze, S., Patterson, B., Higginson, S., 2011. Managed aquifer recharge of treated wastewater: water quality changes resulting from infiltration through the vadose zone. Water Res. 45 (17), 5764–5772.

Bergstrom, C., McKeel, C., Patel, S., 2007. Effects of pH on Algal Abundance: A Model of Bay Harbor, Michigan.

BIS (Bureau of Indian Standards) 10500, 2012. Specification for Drinking Water. Indian Standards Institution, New Delhi, pp. 1–5.

Census India, 2011. Kolar District Population, Karnataka. . https://www.censusindia2011.com/karnataka/kolar-population.html.

CGWB, 2012. Groundwater Information Booklet Kolar District, Karnataka. Ministry of water resource, Central Groundwater Board Bangalore, India.

CGWB, 2020. National complication on dynamic groundwater resources of India. . http://cgwb.gov.in/documents/2021-08-02-GWRA_India_2020.pdf.

CGWB (Kolar district profile), 2009. Ground Water Information Booklet Available at: Microsoft Word KOLAR_BROCHURE.doc (cgwb.gov.in).

Chen, G., Meng, T., Wu, W., Si, B., Li, M., Liu, B., Wu, S., Feng, H., Siddique, K.H., 2023. Evaluating potential groundwater recharge in the unsteady state for deep-rooted afforestation in deep loess deposits. Sci. Total Environ. 858, 159837.

Collins, S.L., Loveless, S.E., Muddu, S., Buvaneshwari, S., Palamakumbura, R.N., Krabbendam, M., Lapworth, D.J., Jackson, C.R., Gooddy, D.C., Nara, S.N.V., Chattopadhyay, S., 2020. Groundwater connectivity of a sheared gneiss aquifer in the Cauvery River basin, India. Hydrogeol. J. 28, 1371–1388.

Crites, R.W., Middlebrooks, E.J., Bastian, R.K., 2014. Natural wastewater treatment systems. CRC press.

Dangar, S., Asoka, A., Mishra, V., 2021. Causes and implications of groundwater depletion in India: a review. J. Hydrol. 596, 126103.

Department of Fishery Sciences, Kolar, 2021. . Available at http://www.fisheries-kolar.com/.

DEIAA, 2019. http://environmentclearance.nic.in/writereaddata/FormB/TOR/ConceptualPlan/30_May_2019_1137552231XT0QJDSODistrictSurveyReportKolar.pdf.

Dihan, M.R., Nayeem, S.A., Roy, H., Islam, M.S., Islam, A., Alsukaibi, A.K., Awual, M.R., 2023. Healthcare waste in Bangladesh: current status, the impact of Covid-19 and sustainable management with life cycle and circular economy framework. Sci. Total Environ. 162083.

Dillon, P., Arshad, M., 2016. Managed aquifer recharge in integrated water resource management. Integrated Groundwater Management. Springer, Cham. pp. 435–452.

El Arabi, N.E., Dawoud, M.A., 2012. Groundwater aquifer recharge with treated wastewater in Egypt: technical, environmental, economic and regulatory considerations. Desalin. Water Treat. 47 (1–3), 266–278.

Engberg-Pedersen, L., 2011. Coping with poverty and institutionalised practices: Tank-irrigated cultivation in Kolar District, Karnataka (No. 2011: 09). Available atDIIS Working Paper.

Eslamian, S., Hedayat, E., Esfahani, S.T., Ostad-Ali-Askari, K., Singh, V.P., Dalezios, N.R., Matouq, M., 2018. The reuse of treated wastewater via groundwater recharge for the development of sustainable water resources. International Journal of Rural Development, Environment and Health Research 2, 62–67. https://doi.org/10.22161/ijreh.2.5.4 ISSN 2456-8678.

ESRI (Environmental systems research institute Land cover), 2017-2022. Land Use Land Cover. . https://www.esri.com/en-us/home.

Ganot, Y., Holtzman, R., Weisbrod, N., Russak, A., Katz, Y., Kurtzman, D., 2018. Geochemical processes during managed aquifer recharge with desalinated seawater. Water Resour. Res. 54 (2), 978–994.

Garg, K.K., Anantha, K.H., Nune, R., Akuraju, V.R., Singh, P., Gumma, M.K., Dixit, S., Ragab, R., 2020. Impact of land use changes and management practices on groundwater resources in Kolar district, southern India. J. Hydrol.: Reg. Stud. 31, 100732.

Garg, S., Motagh, M., Indu, J., Karanam, V., 2022. Tracking hidden crisis in India's capital from space: implications of unsustainable groundwater use. Sci. Rep. 12 (1), 1–17.

GoK (Government of Karnataka), 2016. District irrigation plan – Kolar district. Available atPradhana Mantri Krishi Sinchayee Yojane (PMKSY). https://pmksy.gov.in/AboutPMKSY.aspx.

Goswami, S., Sekhar, M., 2022. Estimation of specific yield of hard-rock aquifers in Upper Cauvery River basin region in India by application of AMBHAS-1D groundwater model (No. EGU22-9975). Copernicus Meetings.

Goswami, S., Sekhar, M., 2022b. Investigation and evidence of high episodic groundwater recharge events in tropical hard-rock aquifers of southern India. Front. Water https://doi.org/10.3389/frwa.2022.960669.

Grinshpan, M., Furman, A., Dahlke, H.E., Raveh, E., Weisbrod, N., 2021. From managed aquifer recharge to soil aquifer treatment on agricultural soils: concepts and challenges. Agric. Water Manag. 255, 106991.

Hasan, M.M., Shenashen, M.A., Hasan, M.N., Znad, H., Salman, M.S., Awual, M.R., 2021. Natural biodegradable polymeric bioadsorbents for efficient cationic dye encapsulation from wastewater. J. Mol. Liq. 323, 114587.

Hasan, M.M., Kubra, K.T., Hasan, M.N., Awual, M.E., Salman, M.S., Sheikh, M.C., Rehan, A.I., Rasee, A.I., Waliullah, R.M., Islam, M.S., Khandaker, S., 2023. Sustainable ligand-modified based composite material for the selective and effective cadmium (II) capturing from wastewater. J. Mol. Liq. 371, 121125.

Hussain, J., Husain, I., Arif, M., Gupta, N., 2017. Studies on heavy metal contamination in Godavari River basin. Appl Water Sci 7 (8), 4539–4548.

Icekson-Tal, N., Avraham, O., Sack, J., Cikurel, H., 2003. Water reuse in Israel-the dan region project: evaluation of water quality and reliability of plant's operation. Water Sci. Technol. Water Supply 3 (4), 231–237.

Islam, A., Teo, S.H., Awual, M.R., Taufiq-Yap, Y.H., 2020. Assessment of clean H2 energy production from water using novel silicon photocatalyst. J. Clean. Prod. 244, 118805.

Islam, A., Teo, S.H., Taufiq-Yap, Y.H., Ng, C.H., Vo, D.V.N., Ibrahim, M.L., Hasan, M.M., Khan, M.A.R., Nur, A.S., Awual, M.R., 2021. Step towards the sustainable toxic dyes removal and recycling from aqueous solution-a comprehensive review. Resour. Conserv. Recycl. 175, 105849.

Jovanovic, N., Bugan, R.D., Tredoux, G., Israel, S., Bishop, R., Marinus, V., 2017. Hydrogeological modelling of the Atlantis aquifer for management support to the Atlantis water supply scheme. Water SA 43 (1), 122–138.

KSNDMC, 2009. http://www.ksndmc.org/.

Karnataka State Natural Disaster Monitoring Centre (2020), https://www.ksndmc.org/ Default.aspx.

Kumar, S., 2016. Soil moisture modelling, retrieval from microwave remote sensing and assimilation in a tropical watershed Doctoral dissertation.

Leavitt, P.R., Findlay, D.L., Hall, R.I., Smol, J.P., 1999. Algal responses to dissolved organic carbon loss and pH decline during whole-lake acidification: evidence from paleolimnology. Limnol. Oceanogr. 44 (3, part 2), 757–773.

Manisha, M., Verma, K., Ramesh, N., Anirudha, T.P., Santrupt, R.M., Das, R., Kumar, M.M., Chanakya, H.N., Rao, L., 2023. Socio-economic impact assessment of large-scale recycling of treated municipal wastewater for indirect groundwater recharge. Sci. Total Environ. 859, 160207.

Marechal, J.C., Dewandel, B., Ahmed, S., Galeazzi, L., Zaidi, F.K., 2006. Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. J. Hydrol. 329 (1–2), 281–293.

Maurya, A., Singh, M.K., Kumar, S., 2020. Biofiltration technique for removal of waterborne pathogens. Waterborne Pathogens. Butterworth-Heinemann, pp. 123–141.

Mazrouaa, A.M., Mansour, N.A., Abed, M.Y., Youssif, M.A., Shenashen, M.A., Awual, M.R., 2019. Nano-composite multi-wall carbon nanotubes using poly (p-phenylene terephthalamide) for enhanced electric conductivity. J. Environ. Chem. Eng. 7 (2), 103002.

McCance, W., Jones, O.A.H., Cendon, D.I., Edwards, M., Surapaneni, A., Chadalavada, S., Wang, S., Currell, M., 2020. Combining environmental isotopes with contaminants of emerging concern (CECs) to characterise wastewater derived impacts on groundwater quality. Water Res. 182, 116036.

Mishra, P., Naik, S., Babu, P.V., Pradhan, U., Begum, M., Kaviarasan, T., Vashi, A., Bandyopadhyay, D., Ezhilarasan, P., Panda, U.S., Murthy, M.R., 2022. Algal bloom, hypoxia, and mass fish kill events in the backwaters of Puducherry, southeast coast of India. Oceanologia 64 (2), 396–403.

Modrzynski, J.J., Aamand, J., Wittorf, L., Badawi, N., Hubalek, V., Canelles, A., Hallin, S., Albers, C.N., 2021. Combined removal of organic micropollutants and ammonium in reactive barriers developed for managed aquifer recharge. Water Res. 190, 116669.

Nandan, M.J., Surinaidu, L., Kumar, D., 2021. Sustainable irrigation and economic development through community participated managed aquifer recharge in water scarce regions of Telangana state — a case study. J. Geol. Soc. India 97, 1294–1299.

Nandanwar, M.A.A., Raut, M.A.Y., Qureshi, M.A.S., Bande, M.C.M., Dhawase, M.J.M., Khobragade, M.M.M., 2020. A Review Paper on Groundwater Recharge by Utilizing Waste Water from Residential Area.

NEERI, National Environmental Engineering Research Institute, 2015. Project Completed, Page - 4 - Water Technology and Management Division/The Official Website of CSIR-National Environmental Engineering Research Institute, Government of India.

NGT, National Green Tribunal, 2019. Available at https://greentribunal.gov.in/sites/default/files/all_documents/4th-report-alongwith-annexures_compressed.pdf.

Ofori, S., Puskacova, A., Ruzickova, I., Wanner, J., 2021. Treated wastewater reuse for irrigation: pros and cons. Sci. Total Environ. 760, 144026.

Okello, C., Tomasello, B., Greggio, N., Wambiji, N., Antonellini, M., 2015. Impact of population growth and climate change on the freshwater resources of Lamu IslandKenya. Water 7 (3), 1264–1290.

Packialakshmi, S., Balaji, S., Kumaresan, T., 2015. Inducing recharge of groundwater by treated waste water—a pilot study in southern Chennai metropolitan area. Indian J. Sci. Technol. 8 (11).

Park, E., Parker, J.C., 2008. A simple model for water table fluctuations in response to precipitation. J. Hydrol. 356 (3–4), 344–349.

Patil, A.V., Mankar, T.S., Motegaonkar, S.S., 2017. Wastewater Renovation using Soil Aquifer Treatment (SAT) System: Case Study of Latur District (Marathwada).

Pedrero, F., Kalavrouziotis, I., Alarcón, J.J., Koukoulakis, P., Asano, T., 2010. Use of treated municipal wastewater in irrigated agriculture—Review of some practices in Spain and Greece. Agric. Water Manag. 97 (9), 1233–1241.

Rahman, M.A., Rusteberg, B., Gogu, R.C., Ferreira, J.L., Sauter, M., 2012. A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. J. Environ. Manag. 99, 61–75.

Ramaiah, S.N., Reddy, R., Reddy, V.J., 2017. Over-exploitation of groundwater, and its impact on phreatic aquifer system, surface water bodies and rural water supply schemes in malur taluk, Kolar District, Karnataka-a case study. Nat. Environ. Pollut. Technol. 16 (2), 599.

Rao, H., Rao, L., Chanakya, H.N., 2021. Fate of heavy metals in sewage and polluted water bodies. Curr. Sci. 121 (1), 109.

Rasel, H.M., Al Mamun, M.A., Hasnat, A., Alam, S., Hossain, I., Mondal, R.K., Good, R.Z., Alsukaibi, A.K., Awual, M.R., 2023. Sustainable futures in agricultural heritage: geospatial exploration and predicting groundwater-level variations in Barind tract of Bangladesh. Sci. Total Environ. 865, 161297.

Saleem, M., Hussain, A., Mahmood, G., 2016. Analysis of groundwater quality using water quality index: a case study of Greater Noida (Region), Uttar Pradesh (UP)India. Cogent Engineering 3 (1), 1237927.

Sekhar, M., Shindekar, M., Tomer, S.K., Goswami, P., 2013. Modeling the vulnerability of an urban groundwater system due to the combined impacts of climate change and management scenarios. Earth Interact. 17 (10), 1–25.

Sharma, S.K., Kennedy, M.D., 2017. Soil aquifer treatment for wastewater treatment and reuse. Int. Biodeterior. Biodegrad. 119, 671–677.

Shawaqfah, M., Almomani, F., Al-Rousan, T., 2021. Potential use of treated wastewater as groundwater recharge using gis techniques and modeling tools in dhuleil-halabat well-field/Jordan. Water 13 (11), 1581.

Singh, C., 2020. Of borewells and bicycles1: the gendered nature of water access in Karnataka, South India and its implications for local vulnerability. Engendering Climate Change. Routledge India, pp. 58–84.

Siva Prasad, Y., Venkateswara Rao, B., 2018. Groundwater recharge estimation studies in a khondalitic terrain of India. Appl. Water Sci. 8 (4), 1–9.

Sivapullaiah, P.V., Kantha, H.L., Kiran, K.M., 2003. Geotechnical properties of stabilised Indian red earth. Geotech. Geol. Eng. 21 (4), 399–413.

Subash, Y., Sekhar, M., Tomer, S.K., Sharma, A.K., 2017. A Framework for Assessment of Climate Change Impacts on Groundwater System Formations. Sustainable water Resources Management, pp. 375–397.

Sunyer-Caldú, A., Benedetti, B., Valhondo, C., Martínez-Landa, L., Carrera, J., Di Carro, M., Díaz-Cruz, M.S., E., 2023. Using integrative samplers to estimate the removal of pharmaceuticals and personal care products in a WWTP and by soil aquifer treatment enhanced with a reactive barrier. Sci. Total Environ. 867, 161466.

Teo, S.H., Ng, C.H., Islam, A., Abdulkareem-Alsultan, G., Joseph, C.G., Janaun, J., Taufiq-Yap, Y.H., Khandaker, S., Islam, G.J., Znad, H., Awual, M.R., 2022. Sustainable toxic dyes removal with advanced materials for clean water production: a comprehensive review. J. Clean. Prod. 332, 130039.

Van Houtte, E., Verbauwhede, J., 2012. Sustainable groundwater management using reclaimed water: the Torreele/St-André case in FlandersBelgium. Journal of Water Supply: Research and Technology—AQUA 61 (8), 473–483.

Veeranna, J., Jeet, P., 2020. Groundwater recharges technology for water resource management: A case study. Groundwater Management and Resources. IntechOpen.

Wakode, H.B., Baier, K., Jha, R., Azzam, R., 2018. Impact of urbanization on groundwater recharge and urban water balance for the city of Hyderabad, India. Int. Soil Water Conserv. Res. 6 (1), 51–62.

Wei, L., Li, S., Noguera, D.R., Qin, K., Jiang, J., Zhao, Q., Kong, X., Cui, F., 2015. Dissolved organic matter removal during coal slag additive soil aquifer treatment for secondary effluent recharging: contribution of aerobic biodegradation. J. Environ. Manag. 156, 158–166.

Wilson, L.G., Quanrud, D., Arnold, R., Amy, G., Gordon, H., Conroy, A.D., 1995. Field and laboratory observations on the fate of organics in sewage effluent during soil aquifer treatment. International Symposium on Artificial Recharge of Ground Water - Proceedings. ASCE, Orlando, FL, USA.

Yaqub, M., Ngoc, N.M., Park, S., Lee, W., 2022. Predictive modeling of pharmaceutical product removal by a managed aquifer recharge system: comparison and optimization of models using ensemble learners. J. Environ. Manag. 324, 116345.

Zaibel, I., Zilberg, D., 2021. Treated municipal wastewater as a water source for sustainable aquaculture: a review. Rev. Aquac. 14 (4).

Zaibel, I., Appelbaum, Y., Arnon, S., Britzi, M., Schwartsburd, F., Snyder, S., Zilberg, D., 2019. The effect of tertiary treated wastewater on fish growth and health: laboratory-scale experiment with poecilia reticulate (guppy). PloS one 14 (6), e0217927.

Zhang, H., Huo, M., Fan, W., Zhu, S., Lu, Y., Xiong, H., Geng, W., Dong, L., 2018. Water quality variation and hydrogeochemical evolution during artificial groundwater recharge with reclaimed water: laboratory experimental and numerical simulation study. Arab. J. Geosci. 11 (13), 1–16.

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Research paper

Cost-benefit analysis of large-scale recycling of treated wastewater for indirect groundwater recharge in a semi-arid region

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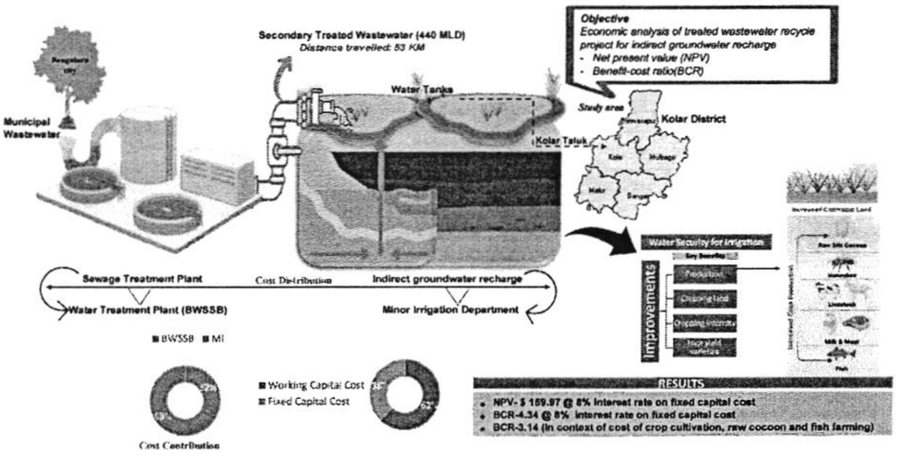
HIGHLIGHTS

- Wastewater recycling (WR) contributes to multiple Sustainable Development Goals −2,3,6.
- WR results in extended cropping season, improved yields, fish production, and revenue.
- The net present value of WR project was $159.97, confirming tangible economic benefits.
- Benefit-cost ratio of WR project for indirect groundwater recharge was 4.34.
- Policy recommendation: achieve improved groundwater levels through WR.

GRAPHICAL ABSTRACT



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ABSTRACT

The large-scale recycling of treated wastewater plays a pivotal role in promoting groundwater sustainability, addressing water scarcity, and ensuring efficient resource utilization to achieve sustainable development goals. This study aimed to conduct a cost-benefit analysis of an innovative large-scale treated wastewater recycling project for indirect groundwater recharge in the Kolar district of Karnataka, India. Data regarding project and cultivation costs were obtained from multiple government organizations. Analysis was based on nine years of agricultural production data (2014–2022). A linear extrapolation was conducted on total production data, using 2018 as a reference point for a business-*as*-usual case, to quantify the benefits resulting from the project. The study's findings indicated a significant expansion in cultivated land and improved productivity due to the water security, leading to an increase in revenues. There was a significant 3-time increase in raw cocoon production and related revenues. Year-round filled tanks resulted in >24-times increase in fish production and revenues. The

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cost-benefit analysis confirmed that the project's benefits exceeded the costs, with a net present value of US$ 159.97 million at 8 % interest rates on fixed capital cost and a benefit-cost ratio (BCR) was 4.34. The BCR in the context of the cost of crop cultivation, raw cocoon, and fish production was 3.14. This indicates substantial economic benefits due to the water recycling project. Furthermore, the recycling project has potential to improve employment opportunities, boost local economy and promote sustainability. Results provide evidence for policymakers to design an integrated framework that includes treated wastewater reuse for groundwater recharge and achieve multiple Sustainable Development goal (SDG), mainly SDG - 2 (Zero hunger), 3 (Good health and well-being) and 6 (water and sanitation for all). This approach encourages circular economies, enhances agro-economic systems, and ensures a sustainable balance between development, agriculture, and resource responsibility in developing countries.

1. Introduction

Water scarcity and declining freshwater pose a growing threat worldwide (Tzanakakis et al., 2020; Lele, 2022; Akbar et al., 2022). In response, treated wastewater reuse has emerged as a promising and sustainable strategy for mitigating water stress in India and many other countries (Icekson-Tal et al., 2003; Tortajada and Bindal, 2020; Chandnani et al., 2022; Manisha et al., 2023a). Wastewater reuse offers a multitude of benefits. It addresses wastewater management challenges, increases water availability, recharges groundwater (GW) resources, and boosts agricultural productivity (Guerra-Rodríguez et al., 2020; Echeverría, 2021; Ofori et al., 2021; Manisha et al., 2023a; Verma et al., 2023a). Additionally, it fosters a circular economy by minimizing environmental impact through reduced wastewater discharge directly into freshwater bodies (Guerra-Rodríguez et al., 2020). However, successful implementation of wastewater reuse projects requires careful consideration of several factors such as environmental and public health safety, socio-cultural acceptance, and economic viability (Breitenmoser et al., 2022; Essahlaoui et al., 2023). Among these, economic feasibility studies through cost-benefit analysis (CBA) play a critical role. CBA is an essential tool used by policymakers to evaluate whether a project is worth investing in, by estimating its costs against its benefits (Hernández-Sancho et al., 2010; Boardman et al., 2017). In the field of wastewater reuse, CBA can play a significant role in the implementation of efficient and effective policies and strategies for wastewater management and reuse to ensure long-term economic, environmental, and social sustainability (Senante- Molinos et al., 2011; Verlicchi et al., 2012; Fan et al., 2015; Al-Sa'ed et al., 2015; Arborea et al., 2017).

While studies explore wastewater reuse for irrigation, GW recharge, and non-potable uses are abundant (Jaramillo and Restrepo, 2017; Aleisa, 2019; Nandan et al., 2021; Ofori et al., 2021; Minhas et al., 2022; Bassi et al., 2022). Jaramillo and Restrepo (2017) focus on

Table 1
Cost-benefit analysis of wastewater reuse project across various countries.

S. No.	Country	Objective: Economic analysis	Economic Indicators	Indicator-Cost	Indicator-Benefit	Remarks	References
1.	Valencia region, Spain	Economic feasibility for wastewater treatment.	Shadow price of undesirable outputs (N, P) obtained from wastewater treatment.	Operation, and maintenance of the project.	Environmental: preventing uncontrolled pollutant dumping provides valuable environmental benefits.	Nutrient removal from wastewater maximizes environmental benefits.	Senante-Molinos et al. (2010)
2.	Po Valley, Italy	Direct reuse of reclaimed wastewater.	Net present value (NPV), benefit-cost ratio (BCR).	Construction of treatment plant, operation, and maintenance cost.	Environmental, and financial benefits.	NPV: € 40,001 BCR: 1.007, financially feasible.	Verlicchi et al., 2012
3.	China, Beijing	Direct reclaimed wastewater reuses.	Net benefit value (NBV), BCR.	Construction of treatment plant, operation, and maintenance cost. Estimation -based on published literature.	Revenues from selling the reclaimed water, water replacement saving for irrigation, environmental improvement, savings of N and P fertilizers.	NBV: € 94.93 million, BCR-1.7, financially feasible.	Fan et al. (2015)
4.	Serbia	Wastewater treatment project with the full cost recovery calculation.	NPV & BCR	Incremental operation and maintenance costs of wastewater services.	Environmental: reduction of pollutant load including N and P -	NPV: € 8.07 million, BCR: 1.64, economical viable.	Djukic et al. (2016)
5.	Puglia, Italy	A methodological framework for cost-benefit analysis to wastewater project.	Cost-benefit comparison.	Upgrading the existing treatment plants, operation, and maintenance.	Treated wastewater for direct irrigation on new land and reduction of groundwater usage (Hypothesized).	Wastewater treatment could improve regional water availability for irrigation.	Arborea et al. (2017)
6.	Puglia, Italy	Economic feasibility study for wastewater treatment.	NPV and internal rate of return (IRR)	Upgradation of treatment plant and operation and maintenance cost.	Environmental: improved water quality for farmers, prevention of the discharge of effluents from secondary treatment into the sea.	Economically advantageous.	Arena et al. (2020)
7.	Trinitapoli, Italy	Environmental impacts and external costs of wastewater reuse in agriculture.	Monetary evaluation of life cycle assessment impact (LCA).	Supply of treated water and environmental cost.	Reduction in freshwater consumption and marine eutrophication.	Economically viable.	Canaj et al. (2021)
8.	Germany	Reuse of brewery wastewater	Monte Carlo method and probability distributions.	Various costs (sludge disposal, energy, freshwater supply, etc.), reverse osmosis unit.	Drinking water from treated wastewater.	Simulations show 77.2% economic viability for brewery wastewater reuse.	Verhuelsdonk et al. (2021)

environmental and technical aspects, while Aleisa (2019) explores social and regulatory challenges. Similarly, Ofori et al. (2021) indicate the benefits and drawbacks of using treated wastewater for irrigation and Nandan et al. (2021) discuss the benefits of GW recharge in irrigation. Bassi et al. (2022) assess the national market potential for treated wastewater reuse and recommend improved governance frameworks. However, all these studies lack a robust economic evaluation, creating a gap in understanding the complete cost-benefit analysis.

Table 1 indicates that few studies have carried out CBA of treated wastewater reuse, mainly focusing on projects in developed countries. While these studies evaluate the benefits of such systems from different perspectives, there is a lack of similar research in developing countries. Senante- Molinos et al. (2010) use shadow prices to assign economic value to environmental impacts during wastewater treatment, highlighting nutrient removal's economic benefit. Senante- Molinos et al. (2011) even developed a methodology for assessing the economic feasibility of phosphorus recovery from wastewater, considering both internal and external costs. Arborea et al. (2017) and Arena et al. (2020) in Italy evaluate the economic value of reclaimed water for irrigation and its positive impact on GW quality. Fan et al. (2015) quantify the tangible benefits from reclaimed wastewater reuse in Beijing, including revenue generation, reduced freshwater use, and fertilizer savings. Lienhoop et al. (2014), Huang et al. (2020), Ye et al. (2020), Canaj et al. (2021), and Ćetković et al. (2022) focus on the economic advantages of irrigation with treated wastewater and the potential for nutrient recovery to improve environmental sustainability. However, a key gap remains in the literature, quantifying the tangible revenue benefits from improved agricultural production due to enhanced water security through indirect GW recharge (Varasree et al., 2024). This study addresses this critical gap in the literature by assessing the tangible economic impact of a large-scale wastewater recycling project known as Koramangala & Challaghatta Valley (K&C Valley) project which aims for indirect GW recharge using secondary treated wastewater (STW) coming from Bengaluru, India to fill surface tanks (irrigation tanks) of the neighboring semi-arid and drought-prone districts of Kolar (Singh, 2020; Manisha et al., 2023a; Verma et al., 2023a). The surface tank water consistently met the standards outlined by the National Green Tribunal (NGT, 2019) for the disposal of treated wastewater into surface water bodies or for land disposal/applications. To further mitigate potential health risks from heavy metals, the water also met the stricter Bureau of Indian Standards (BIS, 2012; Manisha et al., 2023a; Verma et al., 2023a, 2023c). The K&C Valley project has already shown promising outcomes in terms of significant 68–70% improvement in GW levels, improvement in GW quality (hard to soft) after implementation of project (Singh, 2020; Verma et al., 2023a,b,c; Manisha et al., 2023a, 2023b).

The objective of this study is to assess the economic viability of the K&C Valley wastewater recycling project for indirect GW recharge using CBA. The aim includes quantifying i) the public investment in the wastewater recycling project, ii) agricultural costs borne by farmers and iii) stakeholder benefits from increased productivity and sales (agriculture, horticulture, sericulture, fisheries). This study can empower policymakers in water-stressed regions to make informed decisions for future wastewater reuse initiatives, thereby contributing to achieving multiple Sustainable Development Goals (SDGs), specifically, SDG -6 (Clean Water and Sanitation), SDG- 2 (Zero hunger) and SDG- 3(Good Health and Well-being).

2. Methodology

2.1. K&C Valley project and study area

The K&C Valley indirect GW recharge project is unique in its outcomes and is a joint initiative undertaken by the Minor Irrigation Department (MI), the Government of Karnataka, and the Bengaluru Water Supply and Sewerage Board (BWSSB) (water utility board) in March 2018 to address the prolonged and acute drought situation of semi-arid Kolar district, Karnataka (Manisha et al., 2023a; Verma et al., 2023a). The project involves the rejuvenation of a series of existing man-made surface tank cascades and filling them with recycled water coming from Bengaluru, urban areas, and directing it into the GW aquifers through soil aquifer treatment (SAT) method. Around 440 MLD of STW is currently pumped and later distributed by gravity to over 137 irrigation tanks which in turn recharge the GW in the nearby villages (Singh et al., 2020; Manisha et al., 2023a; Verma et al., 2023a). The project encompasses five taluks (sub-unit of a district), namely Kolar, Srinivasapura, Mulabagilu, Bangarapet, and Malur of the Kolar district (Fig. 1). This study, however, is restricted to only Kolar taluk with the following features: geographical area – 64, 210 ha, cultivated area – 30, 215 ha, irrigation tank - 42, total population- 3,85,410 (rural population-2,46,948 and urban population-1,3,8,462), and major occupation-agriculture and associated activities (Kolar district glance, 2017). As part of the recycling project in Kolar taluk, 146 MLD of treated wastewater is distributed into a 42-surface tanks.

2.2. Data collection

2.2.1. Costs of wastewater treatment and water pumping

The K&C Valley treated wastewater recycle project is split into two components, the BWSSB is responsible for establishing the sewage treatment plant (STP) using secondary wastewater treatment technologies to treat municipal wastewater. However, the MI department has played a crucial role in the project by designing and monitoring the project, installing a pumping station and electrical substation, and constructing and renovating the canal. This canal helps pump water into various surface tanks in the Kolar districts. Hence, cost data for the water treatment process was obtained from BWSSB, while water pumping costs were obtained from the MI department (Fig. 2).

2.2.2. Cost of cultivation: crops, raw cocoon, and fish

The link between higher production and increased cultivation costs necessitates a closer look at the specific costs borne by farmers for various crops, including labor, seeds, fertilizers, pesticides, manure, and machinery use (Foster and Rosenzweig, 2011; Srivastava et al., 2017; Roberts et al., 2023). To calculate the CBA, data on cultivation costs per hectare for various crops, including mulberry leaves for the year 2022 was obtained from the Cost of Cultivation Scheme, University of Agricultural Sciences, Bengaluru, a unit under the Directorate of Economics and Statistics (DES) in the Ministry of Agriculture and Farmers Welfare, Government of India. The Department of Sericulture and the Department of Fisheries, Kolar provided data on raw cocoon and fish production for the year 2022, respectively.

Sericulture is an agro business known for being profitable, providing good returns with minimal investment (Altman and Farrell, 2022; Ekka and Bais, 2023). The production of raw cocoons is a crucial aspect of the thriving sericulture industry in Kolar taluk. The Department of Sericulture, Government of Karnataka, supports sericulture through programs like the Catalytic Development Program (CDP) in collaboration with the Central Silk Board, aiming to improve the growth and productivity of sericulture (Kumar et al., 2019). Fish farming assures a prompt return on investment. The state and central government are actively supporting fish farming by providing subsidies (John et al., 2014).

2.2.3. Benefits

Data on the production and average selling price of various crops, sericulture (raw cocoon), and fish was obtained from relevant government organizations in Kolar district, including the Departments of Agriculture, Department of Horticulture, Department of Sericulture, and Department of Fisheries (Fig. 2). The data on production in Kolar taluk was collected for a nine-year period (2014–2022). This data was then categorized into two groups: 'before-recycling' (2014–2018) and 'after-recycling' (2019–2022) period. It's important to note that cultivation

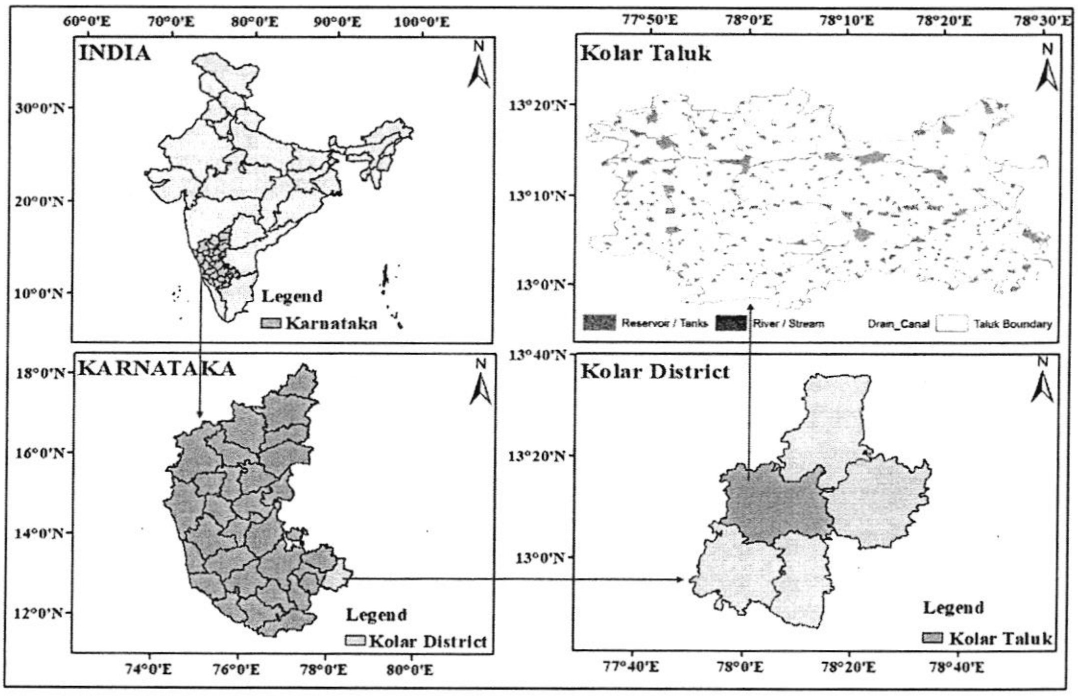

Fig. 1. Drainage network and water bodies within the study area, Kolar taluk, Kolar Karnataka, India.

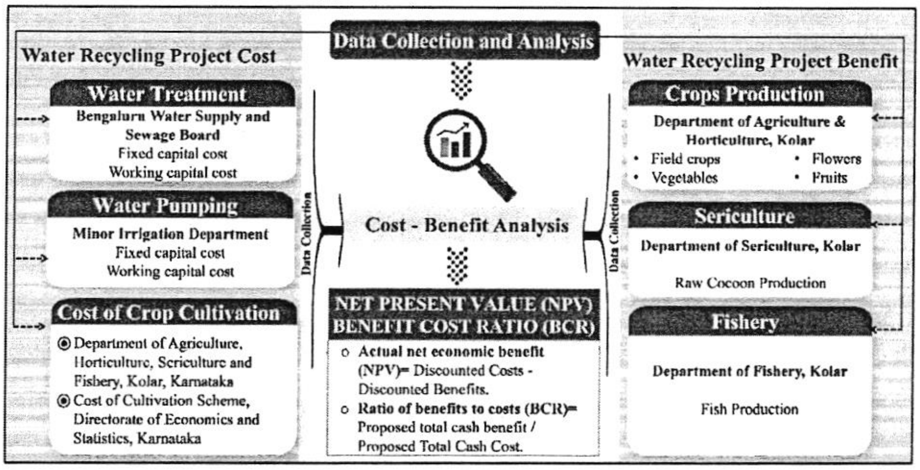

Fig. 2. Methodology for cost-benefit analysis of water recycling project: Data collection and analysis.

practices for different crops, primarily involving seed quality, fertilizer application, and pesticide use, remained consistent before and after the wastewater recycling period. The major change observed was the availability of STW in surface tanks and elevated shallow GW levels due to wastewater recycling. This shift in water availability may have impacted crop cycles and crop selection. Information on these practices was obtained through on-site farmer surveys conducted during visits to the study area. A schematic diagram of the methodology including data collection and analysis has been presented in Fig. 2.

2.3. Data analysis

2.3.1. Cost-benefit analysis (CBA)

In this study CBA was done using conventional methodologies of economic analysis including "Net present value (NPV)" and "Benefit-cost ratio (BCR)" (Hernández-Sancho et al., 2010; Senante- Molinos et al., 2011; Verlicchi et al., 2012; Cellini and Edwin Kee, 2015; Shou, 2022). NPV is a metric used to measure the economic value of the project by calculating the difference between the total discounted benefits and the total discounted costs. In simpler terms, NPV considers the time, and value of money by adjusting for inflation and discounting future cash flows and provides a way to estimate whether the project will generate positive or negative returns over its lifetime (Djukic et al., 2016). The NPV calculation is presented in Eq. (1), where TC and TB are, respectively, the total cost and benefit in the year t, r is the discount rate, and T is the expected plant lifespan. In this study, the selection of the 8% discount rate was based on its alignment with the rate at which the present value of benefits equals the present value of costs (Verlicchi et al., 2012; Simonelli, 2013; Djukic et al., 2016).

The project's cash flows were projected over 25 years, which is deemed to be an appropriate time horizon based on the project's estimated useful life. This time frame allows for a comprehensive assessment of the project's financial performance, considering both capital and operational costs and benefits. By analyzing cash flows over 25 years, decision-makers can more accurately evaluate the project's economic viability and determine whether it aligns with their investment objectives.

$$NPV = \sum_{t=0}^{T} TB(1+r)^{-t} - \sum_{t=0}^{T} TC(1+r)^{-t} \quad (1)$$

Another useful indicator in CBA is the benefit-cost ratio (BCR). It is the ratio of the total present value of benefits and the total present value of costs, presented in Eq. (2).

$$B = \frac{\sum_{t=0}^{T} TB(1+r)^{-t}}{\sum_{t=0}^{T} TC(1+r)^{-t}} \quad (2)$$

A BCR >1 generally indicates a project's economic feasibility, whereas BCR <1 suggests that the project's projected benefits are likely lower than its total costs. Similarly, a negative NPV indicates that a project's discounted benefits are insufficient to recover the initial investment, while a positive NPV suggests the project' s benefits outweigh its costs, making it financially attractive.

In this study, "cost" is defined differently for different stakeholders. Government stakeholders are concerned with the costs associated with implementing the wastewater recycling project, while farmers bear the costs of cultivating various crops using indirect recharged GW. Conversely, when it comes to "benefits", farmers are the stakeholders in both scenarios. Although the government may incur short-term costs to implement policies and programs that benefit farmers, such investments can have long-term benefits for society, including increased food security, improved nutrition, and reduced poverty.

2.3.2. *Cost of wastewater treatment and water pumping*

In the present study, the annualized total cost (ATC) for the project was calculated by combining the ATC of wastewater treatment and water pumping, as presented in Table 2. The costs of wastewater treatment, which were incurred by the BWSSB, include the fixed capital cost (FCC) for constructing the STP. This includes the costs of civil works and electrical and mechanical works (E&M). In addition, the working capital cost (WCC) was considered, which includes the annual operation and maintenance (O&M) cost. These O&M costs include expenses for power, civil repairs, engineering, and maintenance (Engg. & M), chemicals, and manpower. Similarly, the cost of water pumping, which was incurred by the MI department was also calculated including FCC and WCC. However, FCC calculation was based on 8% interest rates (I) for 25 years. The 8% interest rate is a subsidized rate, as established by the Ministry of Finance, Government of Karnataka, in contrast to the prevailing market rate of 15% (Ministry of Finance, 2023). The ATC was calculated as given in the following Eq:3.

$$ATC = (FCC_1 + WCC_1) + (FCC_2 + WCC_2) \quad (3)$$

Where,

$ATC_1 = FCC_1 + WCC_1$; $ATC_2 = FCC_2 + WCC_2$; $ATC_1 = A_1+B_1+C_1+D_1+E_1+F_1+G_1$;

$ATC_2 = A_2+B_2+C_2+D_2+E_2+F_2+G_2$

Note: FCC = fixed capital cost, WCC = working capital cost, ATC = annualized total cost, ATC_1 = annualized total water treatment cost, ATC_2 = annualized total water pumping cost, A = civil work, B = E&M work, C = power, D = civil repair, E = Engg. & M, F = chemicals, G = manpower, 1 = water treatment, 2 = water pumping.

2.3.3. *Agricultural cost: crops, raw cocoon and fish*

The annualized total agricultural production cost (ATAPC) includes the cost of crop cultivation, raw cocoon, and fish production as presented in supplementary file Table S2. ATAPC includes working costs, such as human, animal, and machine labor, seeds, fertilizers, manure, insecticides, irrigation charges, crop insurance, and interest in working capital. Additionally, fixed costs include the rental value of owned land, rent paid for leased-in land, land revenue, taxes, cesses, depreciation on farm machinery, and interest on fixed capital cost at 7% per annum (fixed by the Reserve Bank of India) (DOES, COC, 2022). The ATAPC was calculated as given in the following Eq:4.

$ATAPC = ATCC + ATRPC + ATFPC$ ………………………………………… (4)

Where,

$ATCC = ATWC_1+ATFC_1$; $ATRPC = ATWC_2+ATFC_2$; $ATFPC = ATWC_3+ATFC_3$

$ATWC = H_1+H_2+I_1+I_2+J_1+J_2+K_1+K_2+L_1+L_2+L_3+L_4$

$ATFC = M_1+M_2+N_1+N_2+N_3$

Note: ATAPC = annualized total agricultural production cost, ATCC = annualized total crop cultivation cost, ATRPC = annualized total raw cocoon production cost, ATFPC = annualized total fish production cost, ATWC = annualized total working cost, ATFC = annualized total fixed cost, 1 = crop cultivation, 2 = raw cocoon production, 3 = fish production, H_1 = human labor (family), H_2 = hired human labor, I_1 = hired animal labor, I_2 = owned animal labor, J_1 = hired machine labor, J_2 = owned machine labor, K_1 = seed, K_2 = fertilizer and manure, L_1 =

Table 2
Costs of wastewater treatment and water pumping to surface tanks.

Code	Category	Unit	BWSSB- Annualized water treatment cost/MLD [1]	MI - Annualized water pumping cost/MLD [2]	Annualized total cost/ MLD = (1 + 2)
A	Civil works	USD Thousand/ MLD/Annum	4.4	13.6	18.0
B	E&M works		3	18.2	21.2
Fixed capital cost (FCC) (A + B)	**Fixed capital cost (at 8% I)**		**7.4**	**31.8**	**39.2**
C	Power		4.6	7.6	12.2
D	Civil work repair		1.4	1.4	2.8
E	Engg. & M Repair		0.5	0	0.5
F	Recurring chemicals		0.5	0	0.5
G	Manpower		5.8	2.6	8.4
Working capital cost (WCC) (C + D + E + F + G)	**Total operation and maintenance cost**		**12.8**	**11.6**	**24.4**
Annualized total cost (ATC)/MLD (FCC + WCC)			**20.2**	**43.4**	**63.6**
Annualized total cost/KLD			US$ 0.05	US$ 0.12	US$ 0.17

Note: Annualized meaning 365 days of operation.
The power cost considered is US$ 0.072/kW-hr.
US Doller rate at present value = ₹ 83 only.
Data source: Authors estimate based on data from the BWSSB and MI Department (2018).

insecticides, L_2 = irrigation charges, L_3 = miscellaneous, L_4 = interest on working capital, M_1 = owned land, M_2 = paid for leased-in-land, N_1 = land revenue, taxes, cesses, N_2 = depreciation on own farm machinery, N_3 = interest on fixed capital.

2.3.4. *Benefit analysis*

The presented study focuses on assessing the economic benefits of three critical factors. The economic benefits are estimated by aggregating the revenue generated from the sale of produce in (i) agricultural and horticultural (ii) sericulture (raw cocoon) and (iii) fish-rearing activities. The total crops production was calculated based on the data obtained for the total agricultural crop area, cropping season, and productivity, presented in the supplementary file Table S1.

The crop production data analyzed in this study included three primary types, namely field crops (cereals and pulses), horticultural crops (predominantly vegetables and fruits), and floricultural crops (flowers generally raised for export and domestic uses). This type of grouping was a necessity arising from how data is being collected and managed by governmental departments. Fig. 3 (a) focuses on the dominant crops cultivated in the study area that were selected for benefits analysis. These crops (finger millet, groundnut, green leafy vegetables, tomato, chrysanthemum, marigold, papaya, and mango) account for a significant 77% of the total crop production. Fig. 3 (b) indicates that the selected crops contribute nearly 85% of the total revenue generated by crop production in the study area. This focus on dominant crops ensures the analysis provides valuable and relevant insights for both farmers and policymakers in the overall agricultural sector.

To quantify the comprehensive economic benefits in agriculture resulting from the water recycling project, a linear extrapolation was carried out on total production data, using 2018 as a reference point to establish a business-*as*-usual case (Mühlbach and Reimers, 1987; Liu, 2006; Lewis et al., 2023). Subsequently, the benefits for each sector were calculated by subtracting the estimated production from the business-*as*-usual case from the actual production. Then, the average gross revenue (AGR) difference of production was multiplied by the yearly average market rate received by the Department of Agriculture and Deapartment of Horticulture, Kolar. The AGR was calculated for agriculture and horticulture, sericulture (raw cocoon), and fish production as given in the following Eqs. (5)–(7) respectively (Table 3).

$$X_5 = (X_1 - X_2) * X_4 \ldots \tag{5}$$

$$Y_5 = (Y_1 - Y_2) * Y_4 \ldots \tag{6}$$

$$Z_5 = (Z_1 - Z_2) * Z_4 \ldots \tag{7}$$

Note: X = agriculture and horticulture, Y = raw cocoon, Z = fish, 1 = actual production in 2022, 2 = business as usual, 3 = (1–2) i.e., difference between actual production and business as usual; 4 = selling rate, 5 = average gross revenue.

Finally, Table 3 presents the computation of TB derived from the water recycling project, considering the estimated AGR from the agricultural and horticulture, sericulture, and fishery sectors. This analysis was conducted using Eq. (7)

$$TB = X_5 + Y_5 + Z_5 \ldots \tag{8}$$

To evaluate the economic feasibility of the project over 25 years, the values obtained were used to forecast both the reported revenue and the business-*as*-usual case revenue.

3. Results

3.1. *Costs of wastewater treatment and water pumping*

Table 2 shows that the ATC of the recycling project was US$ 63.6 thousand/MLD at 8% interest rates on the FCC. This cost includes both the cost of wastewater treatment and water pumping to the surface tank. The cost of wastewater treatment was US$ 20.2 thousand, while the cost of water pumping was significantly higher at US$ 43.4 thousand. Fig. 4 indicates that wastewater treatment contributed 32% of the total cost, while water pumping accounted for the remaining 68%. Furthermore, the analysis indicates that WCC had a higher contribution (63%) to water treatment costs, while FCC had a higher contribution (73%) to water pumping costs. Wastewater treatment likely requires a higher WCC during operation due to continuous technology monitoring, maintenance efforts to ensure water quality compliance, and the ongoing costs of chemicals, manpower, and power consumption. However, water pumping involves a significant FCC for setting up new infrastructure and establishing monitoring processes. However, once operational, the major ongoing costs are power consumption, maintenance, and manpower. The cumulative cost distribution of wastewater treatment and pumping shows that fixed capital had the highest contribution at 62%, followed by working capital at 32%. Analysis of WCC reveals that power cost was the biggest contributor at 19%, followed by manpower at 13%. The high-power cost is mainly due to the high energy demands required for operating the water treatment and water pumping stations. The annualized total cost per 1000 L (KL) for the recycling project (water treatment and pumping) was US$ 0.17. Based on per MLD calculations, the annual total cost of treating and pumping 146 MLD of STW that is distributed into 46 surface tanks in the

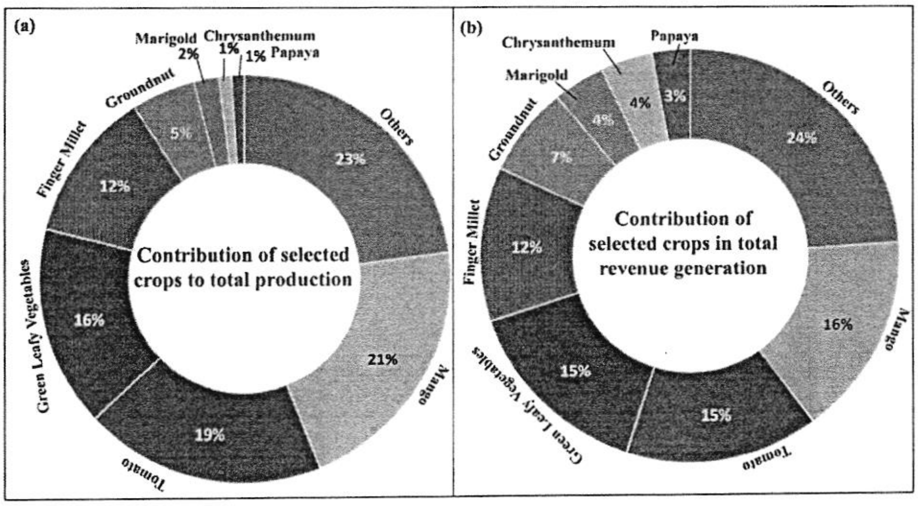

Fig. 3. Contribution of selected crops to (a) total production (b) total revenue generation in Kolar taluk.
Source: Authors estimate based on data from Department of Agriculture and Department of Horticulture, Kolar (2022).

Table 3
Average gross revenue (Benefit) from crops, raw cocoon, and fish production in Kolar taluk.

Sector	Actual Production (Th Tonnes) [1]	Business as usual (Th Tonnes) [2]	Difference in Production (Th Tonnes) [3] = [1]-[2]	Market rates (USD/Kg) [4]	Average gross revenue (AGR) (USD Million) [5] = [3] *[4]
Agriculture and horticulture (crops) [X]	198.60	96.60	102.00	Minimum support price/ wholesale price	21.17
Sericulture (raw cocoon) [Y]	0.41	0.16	0.25	Yearly average rates	1.11
Fishery (raw fish) [Z]	1.90	0.30	1.60	Yearly average rates	3.05
Total benefit (TB) = X5+Y5+Z5					25.33

Data source: Authors estimate based on data from Department of Agriculture, Department of Horticulture, Department of Sericulture and Department of Fisheries (2022).

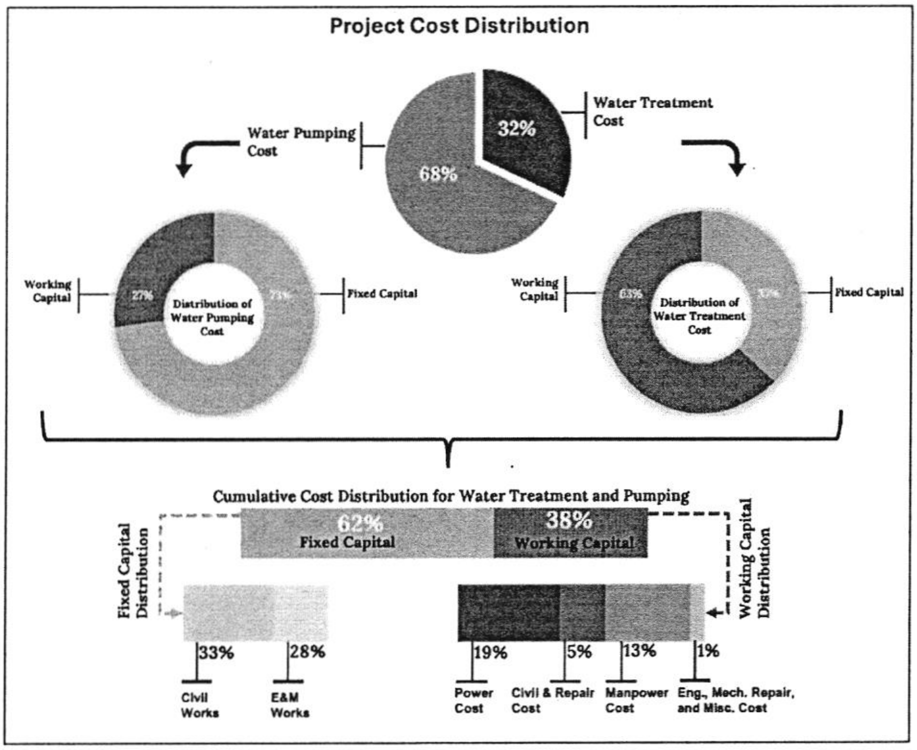

Fig. 4. Water recycling project's cost distribution based on Table 3: Wastewater treatment, water pumping, working capital and fixed capital cost.

study area i.e., Kolar taluk was estimated to be US$ 9.30 million at an 8% interest rate on FCC.

3.2. Cost of cultivation for different crops

ATAPC including cost of cultivation of all types of crops (finger millets, groundnut, green leafy vegetables, tomato, chrysanthemum, marigold, papaya, and mango) and production cost of raw cocoon and fish are presented in the supplementary file (Table S2). However, it's important to note that the cost of cultivation varies based on crop selection. Therefore, detailed crop-wise cultivation costs are provided in the supplementary file (Tables S3–S10). Fig. 5 presents that in 2022, ATAPC was US$ 14.81 million, with share of ATCC at 89% (US$ 13.22 million), ATFPC at 7% (US$ 0.96 million) and ATRPC at 4% (US$ 0.63 million). Further breakdown of ATCC indicates that working capital constituted 76% (US$ 9.98 million) and fixed capital 24% (US$ 3.24 million). Within the working capital, a breakdown reveals human labor as the highest contributor at 29%, followed by seed and nutrients at 20%, machine labor at 15%, others at 10%, and animal labor at 2%. Within the fixed capital, land rental emerged as the predominant contributor, constituting 23% of the share.

Within ATRPC, working capital had the highest contribution in the same period, at 82% (US$ 0.52 million), followed by fixed capital at 18% (US$ 0.11million). The fixed capital of ATFPC contributed 52% (US $ 0.50 million), while working capital contributed 48% (US$ 0.46 million). The high fixed capital cost is likely due to the rental value of the leased surface tanks. The study also calculated the cost of crop cultivation, raw cocoon, and fish production in a business-*as*-usual case to assess cost variations and their impact on the BCR, presented in supplementary file (Table S2). It was noted that the ATAPC is lower in the business-*as*-usual case, amounting to US$ 10.81 million, compared to the actual ATAPC, which stands at US$ 14.81 million.

3.3. Benefits of wastewater recycling project to stakeholders

3.3.1. Increase in cultivated agricultural land

The data presented in Fig. 6 highlights a significant increase in the average crop area cultivated by farmers during after-recycling period compared to before-recycling period. The increase was observed across all crops categories, with the highest increase observed in vegetables, followed by flowers and fruits. The cultivation of vegetables showed the most significant increase of 150%, from 2 thousand (Th) hectare to 5 Th ha. The cultivation of flowers increased by 100%, from 0.5 Th ha to 1 Th ha, while the cultivation of fruits increased by 78%, from 4.5 Th ha to 8 Th ha. In contrast, the cultivation of cereals and pulses showed a comparatively modest increase of only 25%, from 8 Th ha to 10 Th ha.

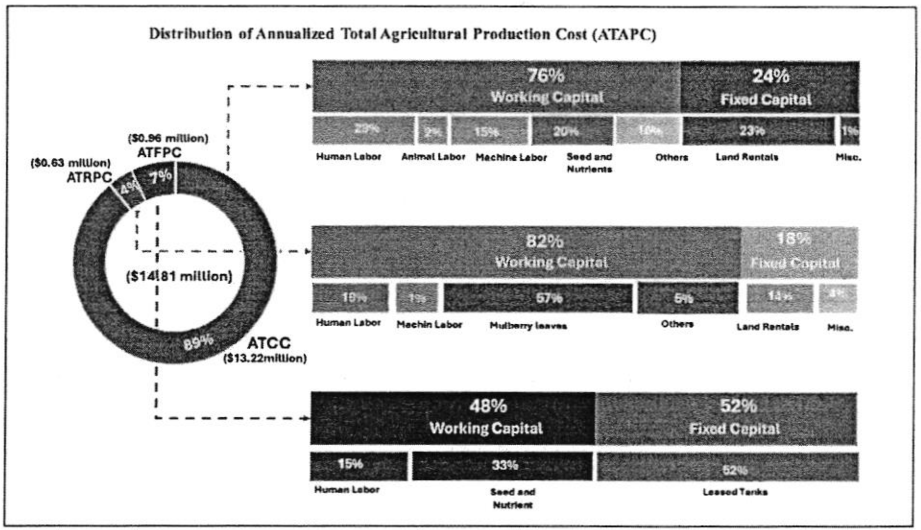

Fig. 5. Annualized total agricultural production cost based on data Table S2: Crop cultivation, raw cocoon, and fish production, working capital and fixed capital. *Note:* ATCC- Annualized total crop cultivation cost; ATRPC- Annualized total raw cocoon production cost; ATFPC- Annualized total fish production cost.
Data source: Authors estimate based on production data from Department of Agriculture, Department of Horticulture, Department of Sericulture, Department of Fisheries, and cost of cultivation data from the Directorate of Economics and Statistics (2022).

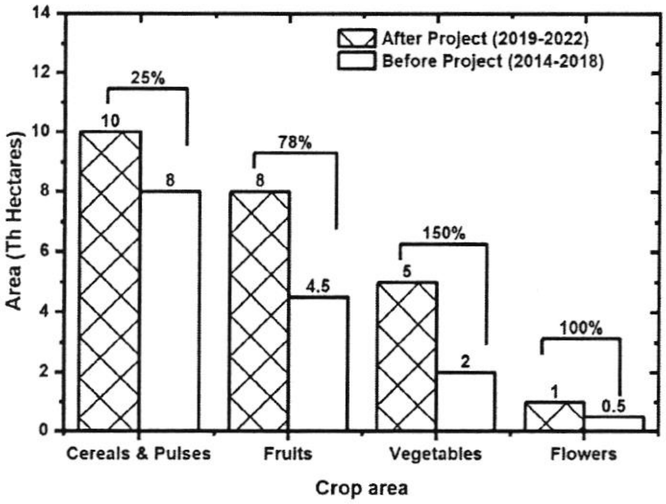

Fig. 6. Comparison in agricultural land use before and after wastewater recycling period in Kolar taluk.
Data source: Department of Agriculture and Department of Horticulture, Kolar (2014–2022).

This increase in crop areas can be explained by the availability of assured water throughout the year, which allowed farmers to convert fallow low-productivity land into productive land. With improved access to water, farmers expanded their cultivated areas and prolonged the cropping season. This allowed them to cultivate multiple crops, including water-intensive and cash crops like vegetables and flowers, which typically offer a quicker return compared to cereals and pulses (Rastegaripour et al., 2024). The improvement in cropping land within the study area is further supported by a previous study conducted in the same region and the annual report of Kolar, Karnataka (ICAR, Krishi Vigyan Kendra, Kolar, 2018; 2022; Manisha et al., 2023a; Verma et al., 2023a). The data highlights the critical role of water availability for irrigation. Increased water access led to both an expansion of cultivated land and an extended cropping season. This assured water supply also empowered farmers to diversify their crops throughout the year, resulting in a significant increase in the total cultivated area.

3.3.2. Comparative analysis of cereal and pulse production and revenue: before, after wastewater recycling period and under business-as-usual case

3.3.2.1. Finger millet. According to Fig. 7 (a), the production of finger millet (also known as Raagi) has increased after-recycling period compared to before-recycling period. Before recycling period, the average annual production of finger millet was nearly 2.52 Th tonnes, but it increased to 8.65 Th tonnes after-recycling period, presenting a ~3-folds increase. The average production increase observed over the business-*as*-usual case was around 66%. This increase in finger millet production has a positive impact on the agricultural economy, as the revenue from finger millet significantly increased. In 2014, the revenue was US$ 1.3 million, which increased to US$ 8 million in 2022, indicating ~ 5- times jump in revenue. Furthermore, the average annual revenue before-recycling period was US$ 1.8 million, which increased to US$ 5.6 million after-recycling period, presenting a ~ 3-folds increase in economic benefit.

This observed increase in production and revenue can be explained by several factors presented in Table S1, including improved average yields per hectare (44%), expansion of the average cropping area (18%), an extended cropping season due to water availability for irrigation and an annual increase of 1.5 times in the minimum selling price (MSP) between before and after-recycling periods. Additionally, there is a noticeable rise in household grain stock, increasing the potential for market sales. These data indicate that the availability of water for irrigation has played a significant role in boosting the production of finger millet and related food security.

3.3.2.2. Groundnut. Fig. 7 (b) indicates that water availability has a significant impact on groundnut production and revenue accrued. The average annual production of groundnut increased from 0.42 Th tonnes to 2.3 Th tonnes, presenting a ~5-folds increase from before-recycling to after-recycling period. However, the average increase in production was around 78% from the business-*as*-usual case. In addition to increased production, a substantial increase in revenue was also observed. Before recycling period, the average annual revenue was US$ 0.8 million. However, after recycling, it jumped to US$ 4.53 million, presenting an almost ~7-folds increase in economic value. The observed increase can be attributed to a combination of three key factors including improved average yields per hectare (81%), expansion of the average cropped area (53%), increase in cropping seasons, and an increase in the MSP between

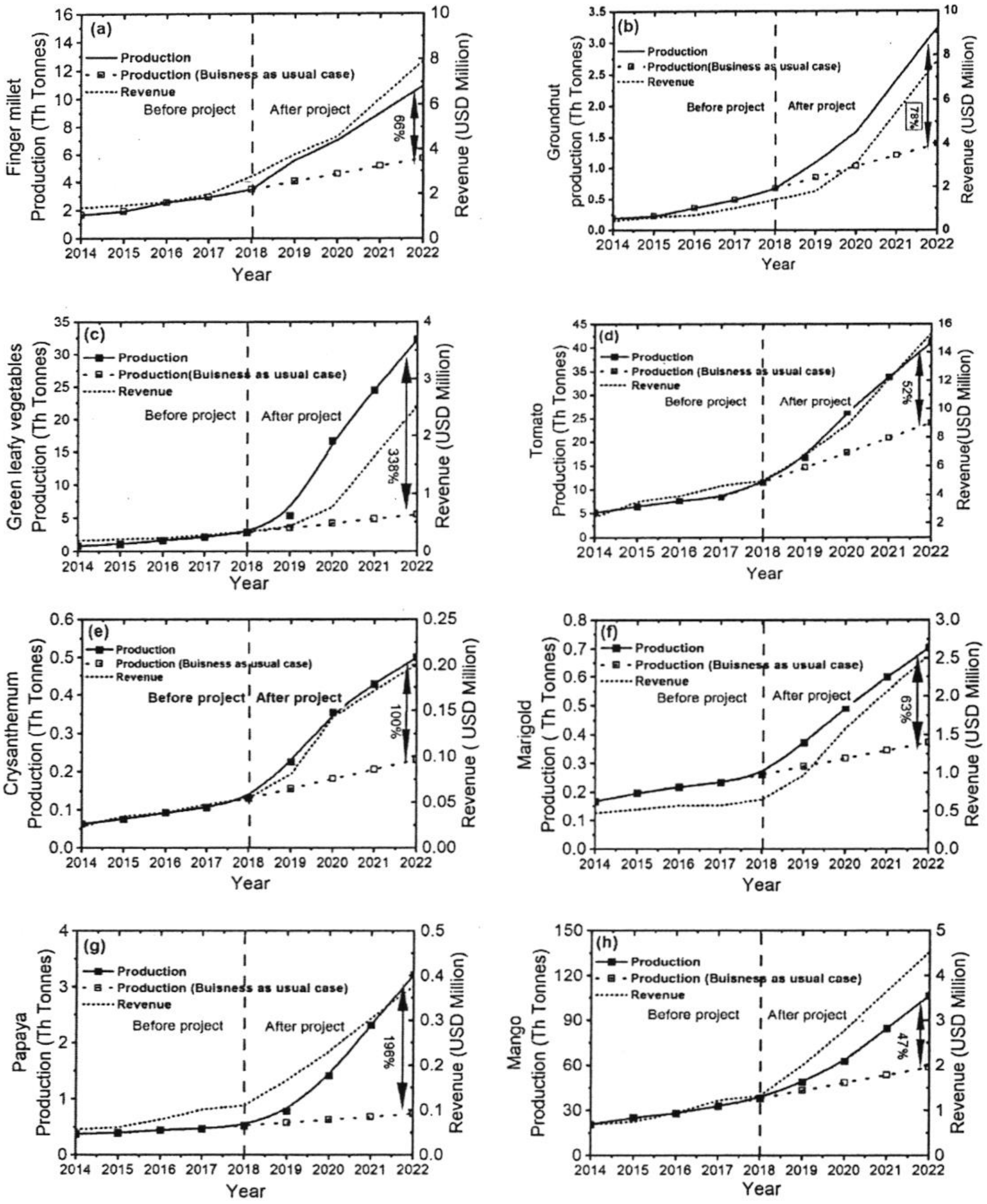

Fig. 7. Pattern of different crop's production and revenue, compared to business-*as*-usual production in Kolar taluk (a) Finger millet (b) Groundnut (c) Green leafy vegetables (d) Tomato (e) Chrysthumum (f) Marigold (g) Papaya (h) Mango.

Data source: [(a) & (b)] Authors estimate based on data from the Department of Agriculture and [(c), (d), (e), (f), (g), (h)] Department of Horticulture, Kolar (2014–2022).

before and after recycling period (Table S1).

3.3.3. *Comparative analysis of vegetable production and revenue: before, after wastewater recycling period and under business-as-usual case*

3.3.3.1. Green leafy vegetable. Fig. 7 (c) shows a significant increase in the production of green leafy vegetables after-recycling period as compared to before-recycling period. Specifically, it was observed that the average annual production of green leafy vegetables was 1.70 Th tonnes before-recycling period, while it increased to 19.26 Th tonnes after-recycling period. This indicates a staggering ~11-folds increase in production. However, the average increase in production was observed to be around 338% over the business-*as*-usual case. Furthermore, the increase in the production of green leafy vegetables has a positive impact on the agricultural economy, as it has resulted in a significant increase in revenue. Before the recycling period, average annual revenue was US$ 0.24 million but after recycling period it reached to US$ 1.35 million, presenting almost 5- times jump in economic benefit. The observed increase can be attributed to a combination of factors presented in Table S1 including improved average yields per hectare (88%), expansion of the average cropped area (100%), cropping season, and an increase in the average annual wholesale price (48%) between before and after recycling period. The data indicates that the availability of irrigation water has played a significant role in boosting the production of green leafy vegetables. By ensuring farmers have a consistent water supply, it becomes feasible for them to cultivate water-intensive crops, including green leafy vegetables, throughout the entire year and even multiple times annually, which reduces the dependence on seasonal variations and weather conditions (Ali and Talukder, 2008; Fischer et al., 2022; Manisha et al., 2023a; Verma et al., 2023a).

3.3.3.2. Tomato. Fig. 7 (d) indicates that the average annual production of tomatoes increased from 7.21 Th tonnes to 33.60 Th tonnes, presenting an almost 5 times increase from before-recycling to after-recycling period. However, the average increase in production was around 52% from the business-*as*-usual case. In addition to increased production, a substantial increase in revenue was also observed. Before recycling period, the average annual revenue was US$ 3.8 million, but after recycling, it jumped to US$ 10.7 million, presenting an almost 3-folds increase in economic profit. The observed increase can be attributed to a combination of various key factors including improved average yields per hectare (20%), expansion of the average cropping areas (62%), increase in cropping seasons (Table S1), and an increase in the average wholesale price (75%) between before and after recycling period.

3.3.4. Comparative analysis of flower production and revenue: before, after the wastewater recycling period and under business-as-usual case

3.3.4.1. Chrysanthemum. Fig. 7 (e) indicates a significant increase in Chrysanthemum production after recycling period. The average annual production before recycling period was 0.07 Th tonnes, but it increased to 0.38 Th tonnes after-recycling period. This means that there was ~5-folds increase in production from before to after recycling period. Furthermore, the data also indicates that there was a 100% increase in average production compared to the business-*as*-usual case. This increase in production has a positive impact on revenue as well. Before recycling period, the average annual revenue generated from Chrysanthemum production was US$ 0.03 million. However, after recycling period, the revenue increased to US$ 0.15 million, which presents an almost 5-folds increase in revenue. It is obvious that the increase in Chrysanthemum production after recycling period is indeed due to an increase in yield per hectare (56%), expansion of the average cropped areas (67%), and improvement in cropping seasons (Table S1) and an increased average wholesale price (21%).

3.3.4.2. Marigold. Fig. 7 (f) presents that the average production of marigolds experienced a significant increase after-recycling period. Specifically, it increased from 0.18 Th tonnes before-recycling period to 0.77 Th tonnes after-recycling, which presents an almost 4-folds increase in overall production. Furthermore, this increase was substantial when compared to the business-*as*-usual case, as it resulted in a 63% jump in production. Furthermore, rise in production was accompanied by a significant improvement in revenue. The average annual revenue of marigolds rose from US$ 0.47 million before recycling to US$ 1.78 million after recycling, indicating a 4-folds increase. The observed increase may be attributed to four key factors, namely, an improvement in average yields per hectare by 67%, an expansion in the average cropped area by 22%, increases in cropping seasons (Table S1), and an increase in the average MSP by 37% between before and after recycling period.

3.3.5. Comparative analysis of fruit production and revenue: before, after the wastewater recycling period and under business-as-usual case

3.3.5.1. Papaya. The data presented in Fig. 7 (g) indicates a significant increase in papaya production before-recycling period. The average annual production of papaya increased from 0.45 Th tonnes before recycling to 2.08 Th tonnes after-recycling period, which is almost a 5-folds increase. This increase in production is even more substantial when compared to the business-*as*-usual case, as it resulted in a 196% jump in production. Furthermore, the increase in papaya production has a significant impact on revenue. The average annual revenue of papaya increased from US$ 0.08 million before recycling to US$ 0.26 million after the recycling period. This presents an almost 3-folds increase in revenue and indicates substantial economic benefits. The observed increase may be explained in terms of increases in average yields per hectare by 66%, cropping area by 37%, extended cropping seasons (Table S1), and growth in average wholesale price by 35% between before and after recycling period. Papaya plants require a consistent supply of moderate watering to support their growth and development. This is demonstrably supported by the observed increase in production and revenue after implementing the wastewater recycling project. These findings align with existing research on the benefits of proper water management for papaya cultivation (Mahouachi and Marrero-Díaz, 2022; Mahouachi et al., 2023).

3.3.5.2. Mango. Mango is the single largest fruit crop raised in Kolar taluk. The data presented in Fig. 7 (h) indicates a significant increase in mango production after-recycling period. Specifically, the average production of mango increased from 27.76 Th tonnes before recycling to 72.14 Th tonnes in the after-recycling period, presenting nearly a 3-folds increase in production. Furthermore, this increase in production resulted in a 47% jump in production compared to the business-*as*-usual case. Moreover, the increase in mango production has a significant impact on revenue. The average annual revenue rose from US$ 0.99 million before recycling to US$ 3.24 million after-recycling period. This presents almost a 3-folds increase in revenue and highlights the economic benefits resulting from the increased mango production. The rise in production and revenue can be explained by the significant increase of 94% in yields per hectare, along with a 34% expansion in cropping areas and a 13% growth in the average wholesale price between before and after recycling period (Table S1).

3.3.6. Comparative analysis of mulberry leaves production: before, after the wastewater recycling period and under business-as-usual case

Fig. 8 (a) indicates that average annual mulberry leaves production increased remarkably from 148 Th tonnes before-recycling period to 306 tonnes after-recycling period. This represents 2-folds rise in mulberry leaves production. Furthermore, due to this increased production, mulberry leaves experienced a significant 44% jump compared to a business-*as*-usual case. The enhanced water availability is expected to extend the mulberry cultivation window, potentially leading to a greater number of mulberry crop cycles per year. This, in turn, could positively impact the number of silkworm cocoon harvests a farm family can undertake annually (Adeduntan, 2015; Bu et al., 2022).

3.3.7. Comparative analysis of raw cocoon production and revenue: before, after the wastewater recycling period and under business-as-usual case

Fig. 8 (b) indicates raw cocoon production in the study area has seen a significant increase after recycling period. Before recycling period, the average annual production of raw cocoon was 0.09 Th tonnes, which increased to 0.29 Th tonnes after-recycling period. This presents a remarkable 3-folds increase in production. Additionally, there was a 49% increase in production as compared to the business-*as*-usual case. This increase in cocoon production has not only contributed to the growth of the sericulture industry but has also generated significant economic benefits. The average annual revenue from raw cocoon production was US$ 0.34 million before recycling period, which increased to US$ 1.16 million after-recycling period. This indicates a 3-folds increase in economic benefit. The increase in raw cocoon production can be attributed to the improvement in the cultivation of mulberry plants and the duration for which leaves can be harvested. The integration of an increase in mulberry and raw cocoon production and revenue shows a positive impact on the local economy and the overall well-being of the community (Barcelos et al., 2021; Mushtaq et al., 2023).

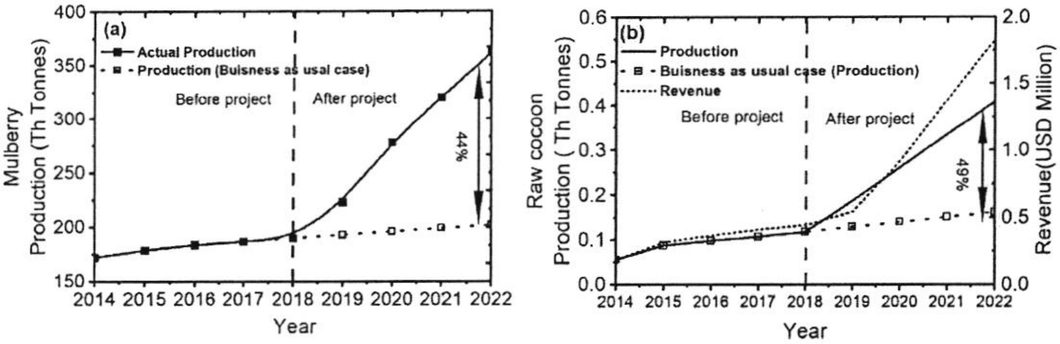

Fig. 8. Pattern of (a) mulberry leaf production (b) raw cocoon production and revenue, compared to business-*as*-usual production in Kolar taluk.
Data source: Authors estimate based on data from the Department of Sericulture, Kolar (2014–2022).

3.3.8. *Comparative analysis of fish production and revenue: before, after the recycling period and under business-as-usual case*

Fig. 9 indicates a significant increase in fish production after-recycling period. Before-recycling period, the average annual fish production (nearly all the fish is caught) was 0.06 Th tonnes, while after-recycling period, it increased significantly to 1.47 Th tonnes, presenting an enormous 24 times increase in production. Compared to the business-*as*-usual case, the production showed a remarkable 525% jump. Moreover, the increase in fish production also has a substantial impact on revenue generation. The average revenue generated from selling fish before-recycling period was US$ 0.10 million, which increased significantly to US$ 2.64 million after-recycling period. This presents a significant 26 times hike in revenue generation.

The improvement in fish production can likely be attributed to several factors, primarily the increased water availability duration in the surface tank. This extended water availability allows for a longer growth period and supports higher stocking densities. The recycled wastewater used in fish farming is richer in phytoplankton, zooplankton, and other nutrients such as nitrogen, phosphorus, and potassium, which are essential for growth of aquatic flora, shelter and multiple trophic levels including increased food for fish growth (Zaibel et al., 2019; Zaibel and Zilberg, 2021; Sukhani and Chanakya, 2020). This combination creates an ideal environment for fish rearing, leading to improved fish growth and production while reducing risks. The growth in fish production has not only improved the overall economic conditions of the region but has also provided a reliable source of income for farmers and livelihoods to laborers involved in the fishing sector.

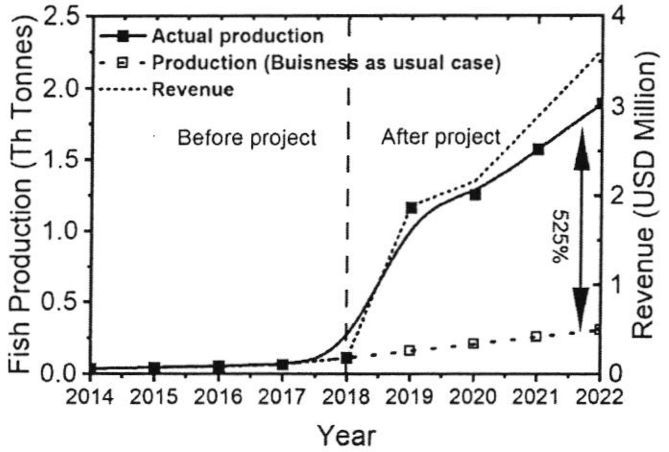

Fig. 9. Pattern of fish production and revenue, compared to business-*as*-usual production in Kolar taluk.
Data source: Authors estimate based on data from the Department of Fisheries, Kolar (2014–2022).

3.4. *Cost-benefit analysis*

3.4.1. *Net present value (NPV)*

In the present study, the various benefits associated with the recycling project are presented in Table 3. This observation revealed that in 2022 the total AGR for the agricultural, sericulture, and fish sectors combined was US$ 25.33 million. That value signifies the difference between the actual revenue and the business-*as*-usual case, serving as an indicator of the positive impact resulting from the recycling project.

Table 4 presents the calculated NPV for the wastewater recycling project. The NPV was US$ 159.97 million at 8% interest rates on FCC, which is greater than 0. The positive NPV provides strong evidence that the wastewater recycling project has the potential to generate long-term

Table 4
Calculation of net present value (NPV) and benefit-cost ratio (BCR) over a 25-year period, from 2018 to 2042.

Year	Unit = USD Million				
	Total benefit (TB)	Total cost (Water treatment and water pumping) (TC)	Discount rate (at 8% I)	PV (TB)	PV (TC)
1	0.00	9.30	0.93	0.00	8.61
2	2.90	4.03	0.86	2.49	3.46
3	8.73	4.03	0.79	6.93	3.20
4	16.27	4.03	0.74	11.96	2.96
5	25.33	4.03	0.68	17.24	2.74
6	25.33	4.03	0.63	15.96	2.54
7	25.33	4.03	0.58	14.78	2.35
8	25.33	4.03	0.54	13.69	2.18
9	25.33	4.03	0.50	12.67	2.02
10	25.33	4.03	0.46	11.73	1.87
11	25.33	4.03	0.43	10.86	1.73
12	25.33	4.03	0.40	10.06	1.60
13	25.33	4.03	0.37	9.31	1.48
14	25.33	4.03	0.34	8.62	1.37
15	25.33	4.03	0.32	7.99	1.27
16	25.33	4.03	0.29	7.39	1.18
17	25.33	4.03	0.27	6.85	1.09
18	25.33	4.03	0.25	6.34	1.01
19	25.33	4.03	0.23	5.87	0.93
20	25.33	4.03	0.21	5.43	0.86
21	25.33	4.03	0.20	5.03	0.80
22	25.33	4.03	0.18	4.66	0.74
23	25.33	4.03	0.17	4.31	0.69
24	25.33	4.03	0.16	3.99	0.64
25	25.33	4.03	0.15	3.70	0.59
			Total	**207.87**	**47.90**
			NPV = 159.97		
			BC Ratio = 4.34		

Note: PV = present value.
Data source: Authors estimate are based on data from Department of Agriculture, Department of Horticulture, Department of Sericulture and Department of Fisheries (2018–2022).

and sustainable economic benefits. This supports the implementation of similar projects to achieve broader social and economic benefits.

3.4.2. Benefit-cost ratio (BCR)

Table 4 presents the details of BCR calculation for the recycling project. At an 8% interest rate on FCC, the recycling project presents a highly favorable BCR of 4.34. This means that for every US dollar invested in the project, there will be a return of US$ 4.34 in benefits. This indicates that the wastewater recycling project is financially viable and has the potential to generate significant returns on investment.

3.4.3. Benefit-cost ratio in the context of annualized total agricultural production cost

The BCR considers ATAPC including crop cultivation, cocoon, and fishery production, (detail presented in supplementary file Table S2) in the denominator and benefits accrued in 2022 (average gross revenue from crops, cocoons, and fish) in the numerator (Table 5). Table 5 indicates that the actual scenario presents a significantly higher BCR of 3.14, compared to 1.96 for the business-*as*-usual case. This impressive increase provides evidence that revenue from agricultural sales significantly outweighs total agricultural costs, even with the added expenses of fertilizer, pesticide cost due expanded cropping land and multiple cropping seasons.

The study's findings provide robust evidence that water availability for adequate irrigation, facilitated by the recycling project, has the potential to significantly improve return on investment in the agricultural sector. This highlights the economic viability and positive impact of water resource management on agricultural productivity and profitability, particularly in water-scarce regions. The project emerges as a crucial driver of agro-economic transformation, promoting a sustainable and prosperous future for agriculture in the study area.

4. Discussion

This study presents a comprehensive CBA using NPV and BCR to evaluate a wastewater recycling project for indirect GW recharge. The project aims to fill existing cascading surface tank networks in semi-arid regions of Kolar district. The analysis confirms the project's economic viability, its potential to generate revenue and societal benefits through increased agricultural production. Findings indicate that after recycling period, agricultural production increased by more than 70% (with variations depending on crops), leading to substantial jumps in farm revenues in Kolar taluk. The increased production is driven by several factors including improved agricultural land (conversion of barren land to productive land), the adoption of multiple cropping seasons and cultivation of water-intensive and cash crops due to water security for timely and adequate irrigation. These findings are supported by a previous study that documented changes in land-use and land cover (LULC) in Kolar district after implementation the recycling project. This analysis revealed a significant increase in water bodies (almost six folds), a dramatic improvement in flooded vegetation areas (67 times), and a 10% reduction in fallow land (Manisha et al., 2023a; Verma et al., 2023a). The improvement in cropping land and crop production is further supported by the annual report of Kolar, Karnataka (ICAR Krish Vigyan Kendra, Kolar, 2018; 2022). The increased crop production aligns with findings from other studies, which suggest that frequent irrigation and maintaining good water quality play a crucial role in improving soil health and supporting the cultivation of crops specially water-intensive crops under climate change conditions (Singh, 2020; Fischer et al., 2022; Verma et al., 2023b, 2023c; Paswan et al., 2024; Rastegaripour et al., 2024). Water stress and hard water have been linked to stunted growth and decreased production of crops (Winter, 2015; Gavrilescu, 2021; Karimi et al., 2024). Studies by Sharma and Kennedy (2017), Ahmad and Al-Ghouti (2020), Raji and Packialakshmi (2022) and Verma et al. (2023a, b) demonstrate that indirect GW recharge improves GW quality through SAT method by reducing electric conductivity, hardness, total dissolved solids, and sodium adsorption ratio values. This transformation occurs as a factor of dilution and additionally recycled water infiltrates through various soil layers (vadose zone) and fractured multi-aquifers. Thus, GW with improved quality (hard to soft) can potentially lead to healthier soil when used for irrigation, particularly by lowering salinity levels (Sharma and Kennedy, 2017; Verma et al., 2023a; Paswan et al., 2024).

Traditionally, the surface tanks in Kolar taluk have functioned as a vital resource for fish cultivation. However, due to prolonged drought conditions before recycling period, water levels in these surface tanks were reliably sustained only from August to January–February, allowing for a mere five-month window for growth. Additionally, significant evaporation losses occur, with approximately 75% of the water volume depleted by January–February. Consequently, the remaining 25% water would sustain a low fish stocking density, leading to suboptimal growth rates and reduced body weight at harvest. However, after recycling period the surface tanks are almost full throughout the year thereby increasing the potential fish growth period to nearly 10–11 months. This also supports higher stocking density as well by providing rapid increase in body weight. Both these factors contribute to 24-folds increase in capacity for fish production.

The CBA demonstrates that the NPV calculated at 8% interest rates on the future cash flows exceeded US$ 159.97 million, indicating positive returns on investment. Furthermore, the BCR was 4.34, confirming that the benefits of the recycling project outweigh the costs. According to Table 2, pumping STW to Kolar tanks has a significantly lower annualized total cost/KLD at US$ 0.17 compared to US$1.00 for pumping the same amount of fresh water. This indicates a cost saving of nearly 83%, demonstrating the project's potential to conserve both financial resources and freshwater. This finding provides evidence that investing in wastewater recycling and reuse projects is a worthwhile endeavor, especially for water-stressed locations. The results of the present study are supported by previous research studies conducted by Godfrey et al. (2009), Birol et al. (2010), Senante- Molinos et al. (2010), Verlicchi et al. (2012), Fan et al. (2015), Al-Sa'ed et al. (2015), Arborea et al. (2017), Omole et al. (2019), Verhuelsdonk et al. (2021) and Bassi et al. (2023) which suggest that investment in reuse of treated wastewater has significant tangible and intangible benefits. Several studies

Table 5
Calculation of BCR in the context of total agricultural production cost.

Sectors	Actual scenario			Business as usual case		
	Total Production (Th Tonnes)	**Average Gross Revenue (AGR) (USD Million)**	**Total Cost (USD Million)**	**Total Production (Th Tonnes)**	**Average Gross Revenue (AGR) (USD Million)**	**Total Cost (USD Million)**
Crop	198.60	41.10	13.22	96.60	19.92	10.26
Raw cocoon	0.41	1.83	0.63	0.16	0.72	0.25
Fish	1.90	3.63	0.96	0.30	0.57	0.30
	BCR=3.14			BCR=1.96		

Data source: Authors estimate based on data from Department of Agriculture, Department of Horticulture, Department of Sericulture, Department of Fisheries (2022).

support the economic viability of wastewater recycling projects. Fan et al. (2015) conducted a CBA of reclaimed water reuse and found a BCR of 1.7, indicating that the benefits were 1.7 times greater than the costs. Similarly, Verlicchi et al. (2012) reported a BCR of 1.007 in their study. Djukic et al. (2016) also analyzed a wastewater treatment project with full cost recovery calculations and obtained a BCR of 1.64 (Table 1). However, this study' s BCR exceeds those of previous studies, indicating wastewater recycling can be especially cost-effective in semi-arid regions. This approach not only improves crop production but also promotes additional income generation through activities like sericulture (silk production) and fisheries.

Beyond the tangible benefits of increased agricultural production and revenue, the wastewater recycling project offers a range of intangible advantages. These include socio-economic benefits such as job creation, improved sanitation and hygiene, and women's empowerment, and market benefits such as improved market accessibility, transaction efficiency, and potentially higher product prices due to enhanced quality (Singh, 2020; Zaman et al., 2022; Manisha et al., 2023a, 2023b; Verma et al., 2023a).

The findings demonstrate that wastewater reuse offers economic advantages beyond cost reductions, playing a role in achieving multiple Sustainable Development Goals (SDGs) including SDG - 2 (Zero Hunger), SDG - 3 (Good Health and Well-being), and SDG - 6 (Clean Water and Sanitation). Treated wastewater replenishes aquifers and leads to improved agricultural production, and income which plays a crucial role in improving socio-economic status, food security, dietary diversity, and nutritional intake at the household level, directly related to SDG - 2 (Foster et al., 2018; Manisha et al., 2023a; Quandt et al., 2023; Verma et al., 2023a). Rising GW tables enhance household water security, enabling improved sanitation and hygiene practices, contributing to the achievement of SDG - 6 (Tortajada, 2020; Gaffan et al., 2022; Obaideen et al., 2022; Manisha et al., 2023b). Furthermore, wastewater reuse for indirect GW recharge not only increases water availability and improves GW quality but also reduces the harmful impacts of direct wastewater discharge on surface water, soil, public and animal health (El Arabi and Dawoud, 2012; Fournier et al., 2016; Al-Hazmi et al., 2023; Verma et al., 2023a). Pollution free GW, improved sanitation and hygiene practices, and enhanced immunity due to food security contribute to SDG - 3 (Bizikova et al., 2020; Munteanu and Schwartz, 2022; Dunbar et al., 2023).

The findings of this study are particularly relevant for developing nations such as Ethiopia, Kenya, Saudi Arabia, Brazil, and Peru have encountered severe water shortages, GW depletion, and substantial gaps in wastewater generation and treatment capabilities (Ioris, 2016; Jones et al., 2021; Nephawe et al., 2021; Lazaro et al., 2023; Vaidya et al., 2023). By examining and adapting similar successful projects, these countries can develop robust strategies for GW recharge and strengthening sustainable and safe agricultural practices. Countries like Maldives, Mauritius, Arizona, Las Vegas, and South Africa can draw insights from the study to enhance water and agricultural resilience, especially in the context of climate change affecting water resources (Melina and Santoro, 2021; Balamurugan et al., 2024). Findings of this study are particularly providing scientific contribution to countries like Brazil and Bangladesh which are seeking economically viable wastewater treatment solutions that are also sustainable and inclusive (Goffi et al., 2018; Kumar et al., 2020; Kligerman et al., 2023).

This study suggests that the economic viability of treated wastewater reuse for indirect GW recharge depends on several key factors. These include the efficacy and cost of treatment technology, infrastructure expenses, and the implementation of stringent water quality control measures, continuous monitoring, and comprehensive impact assessments. The outcomes of this study indicate that wastewater recycling projects present a circular economy, introducing a paradigm shift where cities transform from being mere resource consumers to becoming sources of treated water supplied to villages. This symbiotic relationship not only aids in GW recharge but also enhances agricultural productivity, creating a mutually beneficial resource exchange between cities and villages. These findings can help policymakers with crucial evidence to formulate integrated policies supporting wastewater reuse for indirect groundwater recharge and agricultural development. By offering multi-dimensional benefits across social, economic, and agricultural sectors, this approach justifies investments in wastewater treatment infrastructure and promotes the adoption of reuse practices. This not only promotes sustainable water management but also reduces dependence on freshwater sources for irrigation and other non-potable needs. Eventually, the findings can pave the way for standardized and efficient wastewater reuse practices across India, addressing water scarcity and food security challenges and contributing to SDGs.

5. Limitation and future scope

The presented study highlights tangible economic benefits in agricultural sectors like crop yield, raw cocoon production, and fishery output. However, it is crucial to acknowledge that the associated social and environmental benefits remain largely unquantified. These potential benefits include enhancements in soil quality, reductions in waterborne diseases, employment generation, reverse ruralisation, and biodiversity enhancement.

Therefore, a significant opportunity exists for future research to conduct a more holistic cost-benefit analysis that integrates both tangible and intangible benefits. Potential future directions include expanding the research area to encompass additional GW recharge projects and reassessing the impacts after 10 years of implementation period.

6. Policy recommendation

The reuse of treated wastewater for indirect GW recharge has the potential to meet the growing water demand and generate economic benefits through improved agricultural production and revenue. Economic benefits are crucial for supporting public policy decisions regarding investments in these initiatives. However, decision-making criteria should encompass the broader social and economic benefits. Therefore, to maximize benefits and minimize risks associated with treated wastewater reuse, the study recommends considering the following during decision-making.

- Compliance with stringent water quality standards to ensure the treated wastewater meets safety requirements for indirect GW recharge, minimizing risks of contamination.
- Continuous maintenance and upgradation of technology and STPs to minimize the risk of malfunctions and compromising water quality.
- Implementation of robust monitoring programs to track water quality and environmental impacts that are crucial for evaluating project effectiveness and identifying potential issues or risks.
- Require the establishment of comprehensive risk minimization, risk management, and impact assessment strategies. These strategies should be reviewed every five years to evaluate long-term project sustainability.
- Encourage inter-departmental collaboration between water utilities, agriculture, public health, and community members for project co-ordination and knowledge sharing.
- Develop educational public awareness campaigns in local languages to promote community understanding of the project's benefits, addressing potential concerns and increasing social acceptance.
- Provide training to farmers on safe agricultural practices, including crop selection and risk minimization strategies such as avoiding direct use of treated wastewater for irrigation.
- Tailored approach based on local geography, hydrology and needs for optimizing project design and maximizing long-term benefits.
- Encourage public-private partnerships (PPPs) for financial viability and scalability.

7. Conclusion

This study highlights the economic viability of wastewater recycling projects by demonstrating a positive NPV of US$ 159.97 million and a BCR of 4.34. Economic benefits derived from increased agricultural production and revenue highlight the potential of such projects to drive sustainable development and promote economic growth in water-scarce regions. Moreover, increased agricultural production and revenue directly contribute to achieving SDG - 2. By promoting clean water and sanitation (SDG - 6), this project tackles water scarcity challenges in drought-prone regions. Increased water availability at the household level and reduced wastewater discharge into the environment further contribute to SDG - 3 (Good Health and Well-being). This comprehensive approach aligns with multiple SDGs and informs decision-making processes for the large-scale implementation of such initiatives through effective policy frameworks. This project holds significant potential for generating substantial benefits for communities, businesses, and governments, making them an attractive investment opportunity. This study serves as a comprehensive roadmap for water-scarce nations and regions for GW recharge using STW, outlining innovative and effective strategies that offer a sustainable pathway to tackle multiple challenges simultaneously includingwastewater management, water security, and freshwater use reduction. Ultimately, this approach promotes long-term sustainability and agro-economic development.

CRediT authorship contribution statement

Manjari Manisha: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Kavita Verma:** Writing – review & editing, Formal analysis. Data curation, Conceptualization. **Ramesh N:** Data collecton. **Anirudha TP:** Methodology, Data curation. **Santrupt RM:** Methodology, Formal analysis. **Chanakya HN:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Balachandra Patil:** Writing – review & editing, Methodology. **Mohan Kumar MS:** Writing – review & editing, Methodology. **Lakshminarayana Rao:** Writing – review & editing, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Manjari Manisha reports financial support was provided by Council of Scientific and Industrial Research Human Resource Development Group, New Delhi, India. Dr. Kavita Verma reports financial support was provided by SERB-NPDF,New Delhi, India. Prof. Laxminarayana Rao reports financial support was provided by Minor Irrigation Department, Government of Karnataka, India. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Adeduntan, S.A., 2015. Influence of different varieties of mulberry leaves (Morus alba) on growth and cocoon performance of biovoltine strain of silkworm (Bombyx mori). International Journal of Biological and Chemical Sciences 9 (2), 751–757.

Ahmad, A.Y., Al-Ghouti, M.A., 2020. Approaches to achieve sustainable use and management of groundwater resources in Qatar: a review. Groundwater for sustainable development 11, 100367.

Akbar, H., Nilsalab, P., Silalertruksa, T., Gheewala, S.H., 2022. Comprehensive review of groundwater scarcity, stress and sustainability index-based assessment. Groundwater for Sustainable Development 18, 100782.

Aleisa, E., 2019. Analysis on reclamation and reuse of wastewater in Kuwait. Journal of Engineering Research 7 (1).

Al-Hazmi, H.E., Mohammadi, A., Hejna, A., Majtacz, J., Esmaeili, A., Habibzadeh, S., et al., 2023. Wastewater treatment for reuse in agriculture: Prospects and challenges. Environ. Res., 116711

Ali, M.H., Talukder, M.S.U., 2008. Increasing water productivity in crop production—a synthesis. Agric. Water Manag. 95 (11), 1201–1213.

Al-Sa'ed, R., Yaqob, E., Sorial, G., Suidan, M., 2015. Cost-benefit Analysis Model for Treated Wastewater Use in Agricultural Irrigation: Four Palestinian Case Studies.

Altman, G.H., Farrell, B.D., 2022. Sericulture as a sustainable agroindustry. Cleaner and Circular Bioeconomy 2, 100011.

Arborea, S., Giannoccaro, G., De Gennaro, B.C., Iacobellis, V., Piccinni, A.F., 2017. Cost–benefit analysis of wastewater reuse in Puglia, Southern Italy. Water 9 (3), 175.

Arena, C., Genco, M., Mazzola, M.R., 2020. Environmental benefits and economical sustainability of urban wastewater reuse for irrigation— a cost-benefit analysis of an existing reuse project in Puglia, Italy. Water 12 (10), 2926.

Balamurugan, J., Kasthuri, N., Sudarsan, J.S., Siddi, S., Sakhare, D.T., Sampathkumar, V., 2024. An efficient wastewater collection model for groundwater resource protection in smart cities. Groundwater for Sustainable Development, 101091.

Barcelos, S.M.B.D., Salvador, R., Barros, M.V., de Francisco, A.C., Guedes, G., 2021. Circularity of Brazilian silk: promoting a circular bioeconomy in the production of silk cocoons. J. Environ. Manag. 296, 113373.

Bassi, N., Kumar, S., Kumar, M.D., Van Ermen, S., Campling, P., 2022. Promoting wastewater treatment in India: critical questions of economic viability. Water Environ. J. 36 (4), 723–736.

Birol, E., Koundouri, P., Kountouris, Y., 2010. Assessing the economic viability of alternative water resources in water-scarce regions: combining economic valuation, cost-benefit analysis and discounting. Ecol. Econ. 69 (4), 839–847.

BIS (Bureau of Indian Standards) 10500, 2012. Specification for Drinking Water. Indian Standards Institution, New Delhi, pp. 1–5.

Bizikova, L., Jungcurt, S., McDougal, K., Tyler, S., 2020. How can agricultural interventions enhance contribution to food security and SDG 2.1? Global Food Secur. 26, 100450.

Boardman, A.E., Greenberg, D.H., Vining, A.R., Weimer, D.L., 2017. Cost-benefit Analysis: Concepts and Practice. Cambridge University Press.

Breitenmoser, L., Quesada, G.C., Anshuman, N., Bassi, N., Dkhar, N.B., Phukan, M., et al., 2022. Perceived drivers and barriers in the governance of wastewater treatment and reuse in India: insights from a two-round Delphi study. Resour. Conserv. Recycl. 182, 106285.

Bu, C., Zheng, R., Huang, G., Wu, J., Liu, G., Donald, M.L., et al., 2022. The differences in cocoon and silk qualities among sex-related mulberry and silkworm feeding groups. PLoS One 17 (6), e0270021.

Canaj, K., Mehmeti, A., Morrone, D., Toma, P., Todorović, M., 2021. Life cycle-based evaluation of environmental impacts and external costs of treated wastewater reuse for irrigation: a case study in southern Italy. J. Clean. Prod. 293, 126142.

Cellini, R.S., Edwin Kee, J., 2015. Cost-effectiveness and cost-benefit analysis. Handbook of practical program evaluation 636–672.

Ċetkovic, J., Knežević, M., Lakić, S., Zarković, M., Vujadinović, R., Živković, A., Cvijović, J., 2022. Financial and economic investment evaluation of wastewater treatment plant. Water 14 (1), 122.

Chandnani, G., Gandhi, P., Kanpariya, D., Parikh, D., Shah, M., 2022. A comprehensive analysis of contaminated groundwater: Special emphasis on nature-ecosystem and socio-economic impacts. Groundwater for Sustainable Development, 100813.

Department of Horticulture , Kolar (2022). Available at: https://kolar.nic.in/en/departments/.

Directorate of Economics and Statistics, 2022. Available at: https://desagri.gov.in/en/.

Djukic, M., Jovanoski, I., Ivanovic, O.M., Lazic, M., Bodroza, D., 2016. Cost-benefit analysis of an infrastructure project and a cost-reflective tariff: a case study for investment in wastewater treatment plant in Serbia. Renew. Sustain. Energy Rev. 59, 1419–1425.

DOES, Directorate of Economics and Statistics, 2022. Department of agriculture and family welfare, economic and Statistic Division, cost of cultivation (COC). Karnataka. Available at: https://eands.dacnet.nic.in/Cost_of_Cultivation.htm.

Dunbar, C.L., Aukema, H.M., Calder, P.C., Gibson, D.L., Henrickson, S.E., Khan, S., et al., 2023. Nutrition and immunity: perspectives on key issues and next steps. Appl. Physiol. Nutr. Metabol. 48 (7), 484–497.

Echeverría, J.M.A., 2021. Plan B water assessment: efficiency and circularity for agricultural and municipal adaptation to water scarcity. Groundwater for Sustainable Development 14, 100602.

Ekka, V., Bais, P., 2023. Contribution of sericulture in the socio-economic transformation of the Workers. Asian Journal of Applied Science and Technology 7 (2), 217–224.

El Arabi, N.E., Dawoud, M.A., 2012. Groundwater aquifer recharge with treated wastewater in Egypt: technical, environmental, economical and regulatory considerations. Desalination Water Treat. 47 (1–3), 266–278.

Essahlaoui, F., Elhajrat, N., Halimi, M., El Abbassi, A., 2023. New approach to monitoring a wastewater irrigation system controlled by the artificial neural network (ANN). Groundwater for Sustainable Development 23, 100999.

Fan, Y., Chen, W., Jiao, W., Chang, A.C., 2015. Cost-benefit analysis of reclaimed wastewater reuses in Beijing. Desalination Water Treat. 53 (5), 1224–1233.

Fischer, C., Aubron, C., Trouvé, A., Sekhar, M., Ruiz, L., 2022. Groundwater irrigation reduces overall poverty but increases socioeconomic vulnerability in a semiarid region of southern India. Sci. Rep. 12 (1), 8850.

Foster, A.D., Rosenzweig, M.R., 2011. Are Indian Farms Too Small? Mechanization, Agency Costs, and Farm Efficiency. Unpublished Manuscript, Brown University and Yale University.

Foster, S., Pulido-Bosch, A., Vallejos, A., Molina, L., Llop, A., MacDonald, A.M., 2018. Impact of irrigated agriculture on groundwater-recharge salinity: a major sustainability concern in semi-arid regions. Hydrogeol. J. 26 (8), 2781–2791.

Fournier, E.D., Keller, A.A., Geyer, R., Frew, J., 2016. Investigating the energy-water usage efficiency of the reuse of treated municipal wastewater for artificial groundwater recharge. Environmental science & technology 50 (4), 2044–2053.

Gaffan, N., Kpozehouen, A., Degbey, C., Glèlè Ahanhanzo, Y., Glèlè Kakaï, R., Salamon, R., 2022. Household access to basic drinking water, sanitation and hygiene facilities: secondary analysis of data from the demographic and health survey V, 2017–2018. BMC Publ. Health 22 (1), 1–16.

Gavrilescu, M., 2021. Water, soil, and plants interactions in a threatened environment. Water 13 (19), 2746.

Godfrey, S., Labhasetwar, P., Wate, S., 2009. Greywater reuse in residential schools in Madhya Pradesh, India—a case study of cost-benefit analysis. Resour. Conserv. Recycl. 53 (5), 287–293.

Goffi, A.S., Trojan, F., de Lima, J.D., Lizot, M., Thesari, S.S., 2018. Economic feasibility for selecting wastewater treatment systems. Water Sci. Technol. 78 (12), 2518–2531.

Guerra-Rodríguez, S., Oulego, P., Rodríguez, E., Singh, D.N., Rodríguez-Chueca, J., 2020. Towards the implementation of circular economy in the wastewater sector: challenges and opportunities. Water 12 (5), 1431.

Hernández-Sancho, F., Molinos-Senante, M., Sala-Garrido, R., 2010. Economic valuation of environmental benefits from wastewater treatment processes: an empirical approach for Spain. Sci. Total Environ. 408 (4), 953–957.

Huang, X., Guida, S., Jefferson, B., et al., 2020. Economic evaluation of ion-exchange processes for nutrient removal and recovery from municipal wastewater. npj Clean Water 3, 7.

ICAR (Indian Council of Agricultural Research) Krishi Vigyan Kendra, Kolar (2018, 2022). Annual progress report Available at: https://kvkkolar.karnataka.gov.in/info-4/Annual+Reports/en.

Icekson-Tal, N., Avraham, O., Sack, J., Cikurel, H., 2003. Water reuse in Israel - the Dan Region Project: evaluation of water quality and reliability of plant's operation. Water Supply 3 (4), 231–237.

Ioris, A.A., 2016. Water scarcity and the exclusionary city: the struggle for water justice in Lima, Peru. Water Int. 41 (1), 125–139.

Jaramillo, M.F., Restrepo, I., 2017. Wastewater reuse in agriculture: a review about its limitations and benefits. Sustainability 9 (10), 1734.

John, S., Jagadish, A., Bhatta, R., Sridhar, A., 2014. The state of subsidies: Small-scale Fisher perceptions on subsidies in Karnataka, India. Asian Fish Sci. 27, 45–60.

Jones, E.R., Van Vliet, M.T.H., Qadir, M., Bierkens, M.F.P., 2021. Country-level and gridded estimates of wastewater production, collection, treatment and reuse. Earth Syst. Sci. Data 13 (2), 237–254.

Karimi, M., Tabiee, M., Karami, S., Karimi, V., Karamidehkordi, E., 2024. Climate change and water scarcity impacts on sustainability in semi-arid areas: Lessons from the South of Iran. Groundwater for Sustainable Development 24, 101075.

Kligerman, D.C., Zanatta, A.S., Toledo, G.D.A., Nogueira, J.M.D.R., 2023. Path toward sustainability in wastewater management in Brazil. Int. J. Environ. Res. Publ. Health 20 (16), 6597.

Kolar district glance (2017) Available at: https://kolar.nic.in/en/document/district-at-a-glance-2017-18/.

Kumar, G.A., Reddy, B.S., Goudappa, S.B., Hiremath, G.M., Patil, S.S., 2019. Growth performance of silkworm cocoon production in Karnataka, India. International Journal of Current Microbiology and Applied Sciences 8 (11), 674–682.

Kumar, M.D., Tortajada, C., Kumar, M.D., Tortajada, C., 2020. Wastewater treatment technologies and costs. Assessing Wastewater Management in India 35–42.

Lazaro, L.L.B., Abram, S., Giatti, L.L., Sinisgalli, P., Jacobi, P.R., 2023. Assessing water scarcity narratives in Brazil–Challenges for urban governance. Environmental Development 47, 100885.

Lele, U., 2022. Growing water scarcities: Responses of I ndia and C hina. Appl. Econ. Perspect. Pol. 44 (1), 411–433.

Lewis, A., Montgomery, J., Lewis, M., Randall, M., Schiller, K., 2023. Business as usual versus climate-responsive, Optimised crop Plans–A Predictive model for irrigated agriculture in Australia in 2060. Water Resour. Manag. 37 (6–7), 2721–2735.

Lienhoop, N., Al-Karablieh, E.K., Salman, A.Z., Cardona, J.A., 2014. Environmental cost–benefit analysis of decentralised wastewater treatment and re-use: a case study of rural Jordan. Water Pol. 16 (2), 323–339.

Liu, E.H.L., 2006. Fundamental Methods of Numerical Extrapolation with Applications, vol. 209. Massachusetts Institute of Technology, Mitopencourseware.

Mahouachi, J., Marrero-Díaz, E., 2022. Plant growth and fruit nutrient changes in Carica papaya L. genotypes subjected to regulated deficit irrigation. Life 12 (11), 1831.

Mahouachi, J., Marcelino-Castro, A.D., Álvarez-Méndez, S.J., Urbano-Gálvez, A., 2023. Salicylic Acid applied via irrigation enhances Young Carica papaya L. Plant performance under water deficit. Horticulturae 9 (10), 1070.

Manisha, M., Verma, K., Ramesh, N., Anirudha, T.P., Santrupt, R.M., Das, R., Kumar, M. S., Chanakya, H.N., Rao, L., 2023a. Socio-economic impact assessment of large-scale recycling of treated municipal wastewater for indirect groundwater recharge. Sci. Total Environ. 859, 160207.

Manisha, M., Verma, K., Ramesh, N., Anirudha, T.P., Santrupt, R.M., Rao, L., 2023b. Water, sanitation, and hygiene implications of large-scale recycling of treated municipal wastewater in semi-arid regions. Sci. Total Environ. 904, 166631.

Melina, M.G., Santoro, M., 2021. Enhancing Resilience to Climate Change in the Maldives. International Monetary Fund.

Minhas, P.S., Saha, J.K., Dotaniya, M.L., Sarkar, A., Saha, M., 2022. Wastewater irrigation in India: current status, impacts and response options. Sci. Total Environ. 808, 152001.

Ministry of Finance, Government of Karnataka, 2023. Available at: https://ksfc.karnataka.gov.in/storage/pdf-files/KSFC%20Brochure/Eng_Broc_141016_25202677.pdf.

Mühlbach, G., Reimers, L., 1987. Linear extrapolation by rational functions, exponentials and logarithmic functions. Journal of computational and applied mathematics 17 (3), 329–344.

Munteanu, C., Schwartz, B., 2022. The relationship between nutrition and the immune system. Front. Nutr. 9, 1082500.

Mushtaq, R., Qadiri, B., Lone, F.A., Raja, T.A., Singh, H., Ahmed, P., Sharma, R., 2023. Role of sericulture in achieving sustainable development goals. Problemy Ekorozwoju 18 (1).

Nandan, M.J., Surinaidu, L., Kumar, D., 2021. Sustainable irrigation and economic development through community Participated managed aquifer recharge in water scarce regions of Telangana state — a case study. J. Geol. Soc. India 97, 1294–1299.

Nephawe, N., Mwale, M., Zuwarimwe, J., Tjale, M.M., 2021. The impact of water-related challenges on rural communities food security initiatives. AGRARIS: Journal of Agribusiness and Rural Development Research 7 (1), 11–23.

NGT, National Green Tribunal, 2019. Available at https://greentribunal.gov.in/sites/default/files/all_documents/4th-report-alongwith-annexures_compressed.pdf.

Obaideen, K., Shehata, N., Sayed, E.T., Abdelkareem, M.A., Mahmoud, M.S., Olabi, A.G., 2022. The role of wastewater treatment in achieving sustainable development goals (SDGs) and sustainability guideline. Energy Nexus 7, 100112.

Ofori, S., Puškácová, A., Růžičkova, I., Wanner, J., 2021. Treated wastewater reuse for irrigation: Pros and cons. Sci. Total Environ. 760, 144026.

Omole, D.O., Jim-George, T., Akpan, V.E., 2019. Economic analysis of wastewater reuse in Covenant University. In: Journal of Physics: Conference Series. vol. 1299. IOP Publishing, 012125. No. 1.

Paswan, A.K., Tiwari, V.M., Agarwal, A., Asoka, A., Rangarajan, R., Ahmed, S., 2024. Long-term spatiotemporal variation in groundwater recharge in the highly irrigated semi-arid region of India: the intertwined relationship between climate variability and anthropogenic activities. Groundwater for Sustainable Development 25, 101148.

Quandt, A., Larsen, A.E., Bartel, G., Okamura, K., Sousa, D., 2023. Sustainable groundwater management and its implications for agricultural land repurposing. Reg. Environ. Change 23 (4), 120.

Raji, V.R., Packialakshmi, S., 2022. Assessing the wastewater pollutants retaining for a soil aquifer treatment using batch column experiments. Civil Engineering Journal 8 (7), 1482–1491.

Rastegaripour, F., Tavassoli, A., Babaeian, M., Fernández-Gálvez, J., Caballero-Calvo, A., 2024. Assessing the impacts of climate change on water resource management and crop patterns in Eastern Iran. Agric. Water Manag. 295, 108774.

Roberts, M., Hawes, C., Young, M., 2023. Environmental management on agricultural land: cost benefit analysis of an integrated cropping system for provision of environmental public goods. J. Environ. Manag. 331, 117306.

Senante- Molinos, M., Hernández-Sancho, F., Sala-Garrido, R., 2010. Economic feasibility study for wastewater treatment: a cost–benefit analysis. Sci. Total Environ. 408 (20), 4396–4402.

Senante- Molinos, M., Hernández-Sancho, F., Sala-Garrido, R., 2011. Cost–benefit analysis of water-reuse projects for environmental purposes: a case study for Spanish wastewater treatment plants. J. Environ. Manag. 92 (12), 3091–3097.

Sharma, S.K., Kennedy, M.D., 2017. Soil aquifer treatment for wastewater treatment and reuse. Int. Biodeterior. Biodegrad. 119, 671–677.

Shou, T., 2022. A literature review on the net present value (NPV) valuation method. In: 2022 2nd International Conference on Enterprise Management and Economic Development (ICEMED 2022). Atlantis Press. pp. 826–830.

Simonelli, F., 2013. The role of the discount rate in cost–benefit analysis between theory and practice: a comparative survey. European Journal of Risk Regulation 4 (1), 59–71.

Singh, U.V., 2020. The recycling of sewage generated in Kormanagala-Chellaghtta valley of Bengaluru India. Adv. Environ. Waste Manag. Recycl. 3 (2), 47–62. ISSN: 2641-1784.

Srivastava, S.K., Chand. R., Singh, J., 2017. Changing crop production cost in India: Input prices, substitution and technological effects. Agric. Econ. Res. Rev. 30 (conf), 171–182.

Sukhani, S., Chanakya, H., 2020. Use of sewage to Restore man-made Waterbodies—nutrient and energy flow regulation Approaches to enabling sustainability. In: Ghosh, S., Saha, P., Francesco Di, M. (Eds.), Recent Trends in Wastewater Treatment and Water Resource Management. Springer, Singapore.

Tortajada, C., 2020. Contributions of recycled wastewater to clean water and sanitation Sustainable Development Goals. NPJ Clean Water 3 (1), 22.

Tortajada, C., Bindal, I., 2020. Water reuse in Singapore: the new Frontier in a framework of a circular economy. Water Reuse within a Circular Economy Contex 2. Available at: Water_reuse_in_Singapore_The_new_frontier_in_a_framework_of_a_circular_economy-with-cover-page-v2.pdf (d1wqtxts1xzle7.cloudfront.net.

Tzanakakis, V.A., Paranychianakis, N.V., Angelakis, A.N., 2020. Water supply and water scarcity. Water 12 (9), 2347.

Vaidya, R., Verma, K., Kumar, M., Hoysall. C., Rao, L., 2023. Assessing wastewater management challenges in developing countries: a case study of India, current status and future scope. Environ. Dev. Sustain. 1–28.

Varasree. B., Kavithamani, V., Chandrakanth, P., Padmapriya. R., 2024. Wastewater recycling and groundwater sustainability through self-organizing map and style based generative adversarial networks. Groundwater for Sustainable Development, 101092.

Verhuelsdonk, M., Glas, K., Parlar, H., 2021. Economic evaluation of the reuse of brewery wastewater. J. Environ. Manag. 281, 111804.

Verlicchi, P., Al Aukidy, M., Galletti, A., Zambello, E., Zanni, G., Masotti, L., 2012. A project of reuse of reclaimed wastewater in the Po Valley, Italy: Polishing sequence and cost benefit analysis. J. Hydrol. 432, 127–136.

Verma, K., Manisha, M., Nu, S., Rm, S., Tp, A., Ramesh, N., et al., 2023b. Investigating the effects of irrigation with indirectly recharged groundwater using recycled water on soil and crops in semi-arid areas. Environmental Pollution. 122516.

Verma, K., Manisha, M., Santrupt, R.M., Anirudha. T.P., Goswami, S., Sekhar, M.N., Ramesh, Kumar, M.S., Chanakya, H.N., Rao, L., 2023a. Assessing groundwater recharge rates, water quality changes, and agricultural impacts of large-scale water recycling. Sci. Total Environ. 877, 162869.

Verma, K., Thattaramppilly, R.M., Manisha, M., Jayakumar, S., Marigoudar, S.R., Pranesh, A.T., Rao, L., 2023c. Determination of degradation/reaction rate for surface water quality of recycled water using Lake2K model for large-scale water recycling. Environ. Sci. Pollut. Control Ser. 30 (57), 120207–120224.

Winter, K., 2015. Effects of irrigation water quality on vegetables Part 1: yield and aesthetical appeal. S. Afr. J. Plant Soil 32 (1), 27–31.

Ye, Y., Ngo, H.H., Guo, W., Chang, S.W., Nguyen, D.D., Zhang, X., et al., 2020. Nutrient recovery from wastewater: from technology to economy. Bioresour. Technol. Rep. 11, 100425.

Zaibel, I., Zilberg, D., 2021. Treated municipal wastewater as a water source for sustainable aquaculture: a review. Rev Aquac 14 (4).

Zaibel, I., Appelbaum, Y., Arnon, S., Britzi, M., Schwartsburd, F., Snyder, S., Zilberg, D., 2019. The effect of tertiary treated wastewater on fish growth and health: Laboratory-scale experiment with Poecilia reticulata (guppy). PLoS One 14 (6), e0217927.

Zaman, S., uz Zaman, Q., Zhang, L., Wang, Z., Jehan, N., 2022. Interaction between agricultural production, female employment, renewable energy, and environmental quality: policy directions in context of developing economies. Renew. Energy 186, 288–298.