

Towards a new paradigm of urban water infrastructure: Identifying goals and strategies to support multi-benefit municipal wastewater treatment

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Introduction

The following Figures and Tables provide more detailed results and supporting quotations for the results explained in the main text.

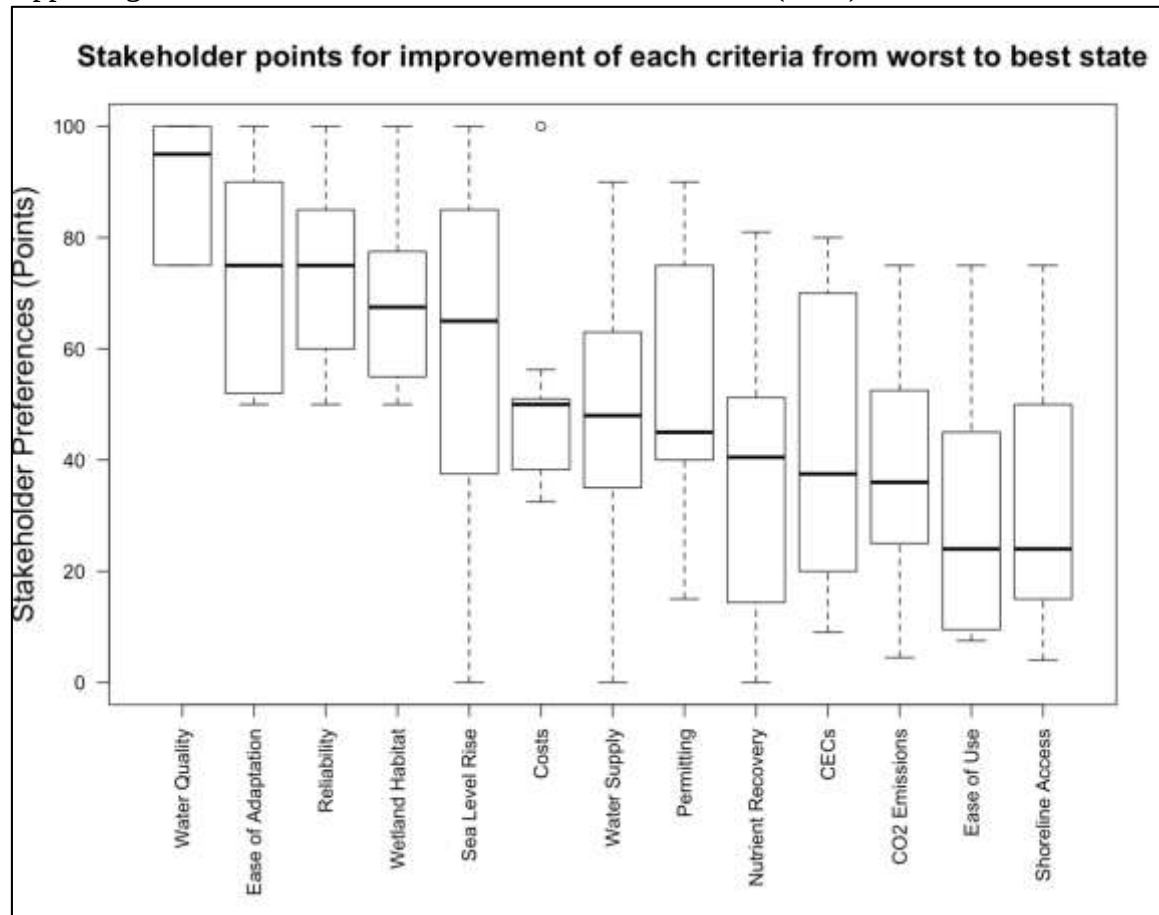


Figure S1. Stakeholder points for improvement of fulfillment of criteria for nutrient management from the worst to the best state, on a scale from 0 (*not at all important*) to 100 (*most important*). Boxplots denote results from the 9 stakeholders who participated in follow-up interviews.

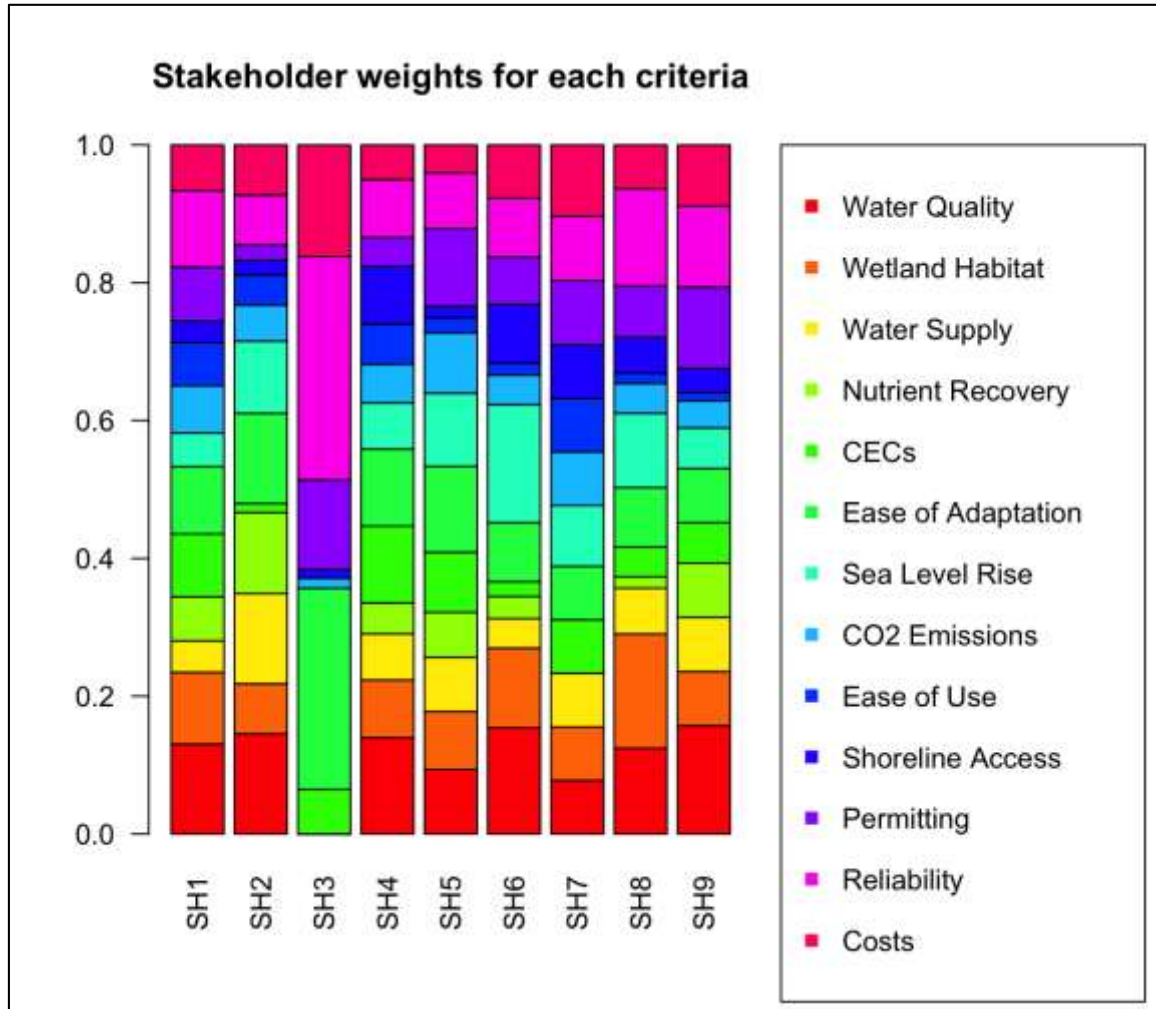


Figure S2. Stakeholder weights for criteria for nutrient management, on a scale of 0 (*not important to decision-making*) to 1 (*most important to decision-making*).

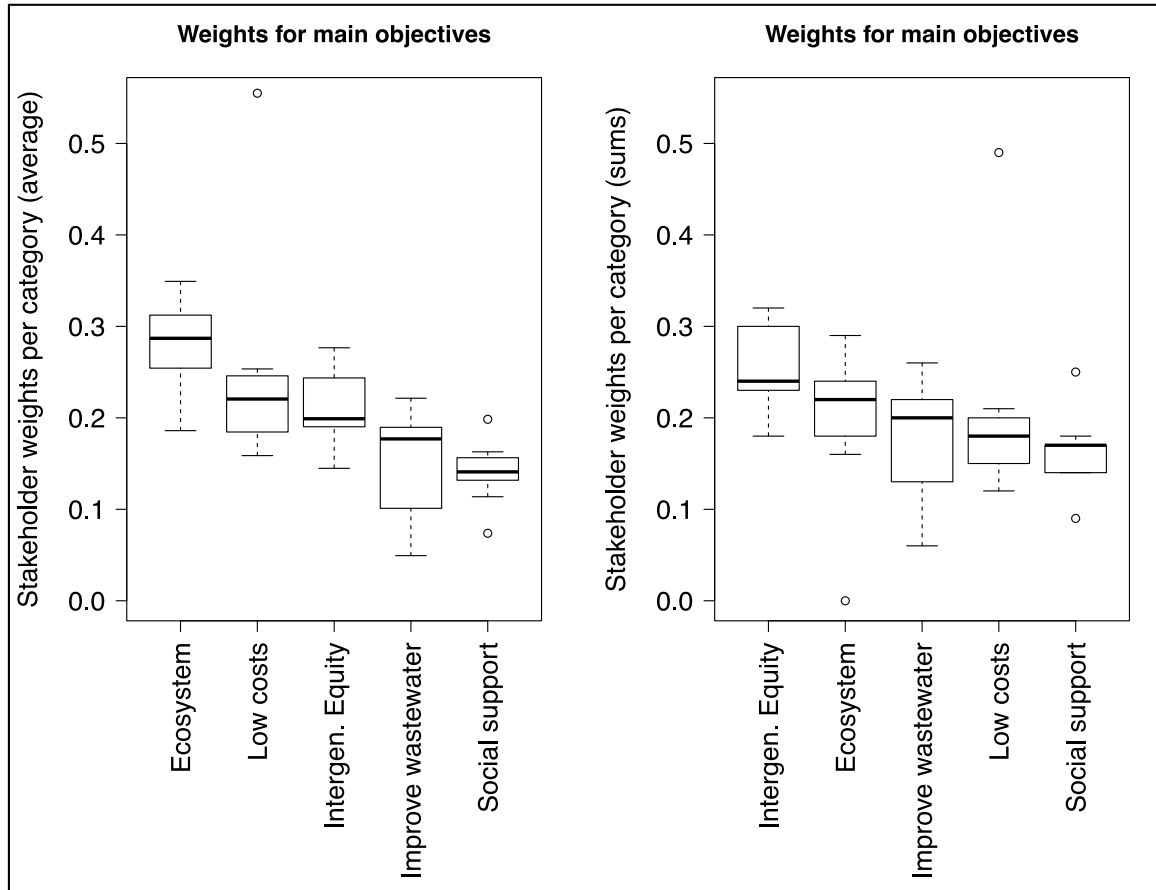


Figure S3. Stakeholder weights of main objective categories for nutrient management. The figure on the left shows the average weight of sub-objectives per category, and the figure on the right shows the summed weight of sub-objectives within each category for the stakeholders.

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Table S1. List of stakeholders, their professional role, and their relevance to decision-making about nutrient management. Stakeholders marked with an asterisk (*) participated in a second interview.

Professional roles defined as: *Advocate* = Supports the interests of a particular cause or group through legal means, public outreach, and/or political lobbying; *Discharger* = Part of an organization that discharges nutrients to the Bay from a point-source like a wastewater treatment plant, as specified in the 2014 nutrient watershed permit (San Francisco Bay Regional Water Quality Control Board, 2014); *Engineer* = Designs and builds technologies for wastewater treatment; *Planner* = Determines, designs, and/or controls construction and development of the Bay and shoreline areas; *Regulator* = Responsible for setting and enforcing legal regulations about environmental conditions; *Researcher* = Conducts scientific studies and analyses of ecological conditions in and around the Bay; *Steward* = Manages land and/or habitat area in and around the Bay; *Water supplier* = responsible for obtaining and distributing municipal water supply.

Relevance defined as: 1 = directly involved in decision-making; 2 = strongly affected by decision-making about nutrients, or with strong influence over those involved in decision-making; 3 = affected by decision-making about nutrients but would not have to make fundamental changes to daily work, 4 = interested/concerned about nutrients, but not directly affected by decision-making.

Stakeholder ID	Professional Role	Relevance to Decision-Making
SH1*	advocate	1
SH2*	discharger	1
SH3*	discharger	1
SH4*	regulator	1
SH5*	regulator	1
SH5*	steward	3
SH7*	discharger	1
SH8*	advocate	1
SH9*	regulator	1
SH10	regulator	1
SH11	planner	4
SH12	regulator	1
SH13	regulator	1
SH14	regulator	4
SH15	water supplier	4
SH16	regulator	2
SH17	advocate	4
SH18	researcher, advocate	2
SH19	discharger	2
SH20	researcher, steward	4
SH21	discharger	2
SH22	discharger	1
SH23	engineer	2
SH24	researcher	4
SH25	steward, researcher	3
SH26	water supplier	3
SH27	regulator	2
SH28	discharger	1
SH29	engineer, planner, regulator	4
SH30	discharger	2
SH31	engineer, planner, regulator	4
SH32	discharger	1

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Table S2. Respondents' stated goals for good nutrient management, research classification of goals, and how stated goals informed the development of the objectives hierarchy and MCDA. (Note: where several respondents stated a goal in very similar or identical terms, it is only shown once here.).

Goal	Goal Classification	Placement in Objectives Hierarchy
"Nimble, quick to change"	Ease of adaptation	Flexible system adaptation
"Adaptively manage all actions"	Ease of adaptation	Flexible system adaptation
"Regularly review and update science and actions"	Ease of adaptation	Flexible system adaptation
"Low sunk costs"	Ease of adaptation	Flexible system adaptation
"Balances not doing anything until it's conclusively proven and the precautionary principle. Those two can meet if done well, in an adaptive management framework"	Ease of adaptation	Flexible system adaptation
"Ability to upgrade nutrient removal from a low level of reduction to a higher level of reduction"	Ease of adaptation	Flexible system adaptation
"Understand ecological effects of nutrient loading in each sub-embayment"	Sound science	Outside the scope of the objectives hierarchy
"Get the loads right"	Sound science	Outside the scope of the objectives hierarchy
"Understand nutrient dynamics – what are the contributions from the benthic environment?"	Sound science	Outside the scope of the objectives hierarchy
"Understand all effects of management actions"	Sound science	Addressed by measuring attributes for all objectives in the MCDA
"Consider non-point sources in addition to point sources"	Sound science	Less relevant in the southern reach of the Bay, where the vast majority of loading is from point sources
"Set a realistic baseline of nutrient levels in the Bay"	Sound science	Outside the scope of the objectives hierarchy
"Avoid premature regulatory action"	Sound science	Outside the scope of the objectives hierarchy
"Use innovative technology based on research"	Sound science	Addressed by considering non-traditional technologies (e.g., wetlands for wastewater treatment, urine source-separation) in the MCDA
"Consider future conditions like climate change, other regulations, and population change"	Sound science/MCDA/Climate concerns	Addressed by considering effects of future uncertainties on MCDA results
"It should make sense to the public"	Public support	Public ease of use

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Goal	Goal Classification	Placement in Objectives Hierarchy
"Should be natural looking and feeling"	Public support	Beautiful Bay and shoreline access
"A sense that the community is receiving the benefits of the investment"	Public support	Beautiful Bay and shoreline access
"Visible, tangible benefits to the people that are paying for it"	Public support	Beautiful Bay and shoreline access
"Doesn't disrupt the public's enjoyment of the shoreline"	Public support	Beautiful Bay and shoreline access
"Should be well-funded"	Public support	Outside the scope of the objectives hierarchy
"Have a clear definition of the problem"	MCDA	Addressed in the stakeholder analysis portion of the MCDA process
"Understand a range of management alternatives"	MCDA	Addressed in the MCDA process
"Stakeholders should provide input"	MCDA	Addressed in the stakeholder analysis portion of the MCDA process
"Balance nutrients with other long-term planning"	MCDA	Addressed in the MCDA process
"Identify short term 'no regrets' actions"	MCDA/Low costs	Addressed in the MCDA process
"Technology should be easy to operate"	Reliability/Low costs	Technical reliability/ Minimize initial capital investment and operations/maintenance costs
"Reliably achieves desired nutrient removal"	Reliability	Technical reliability
"Should be reliable, can decently meet our treatment requirements"	Reliability	Technical reliability
"Low cost"	Low costs	Minimize initial capital investment and operations/maintenance costs
"Consider low-hanging fruit"	Low costs	Minimize initial capital investment and operations/maintenance costs
"Is economically efficient by using funds regionally"	Low costs	Minimize initial capital investment and operations/maintenance costs
"Costs less to operate"	Low costs	Minimize initial capital investment and operations/maintenance costs
"Good water quality in the Bay"	Good water quality	Maximize water quality
"Results in the Bay being ecologically stable and resilient"	Good water quality	Maximize water quality
"Supports fish habitat"	Good water quality	Maximize water quality
"Protects public health"	Good water quality	Maximize water quality
"Maintains dissolved oxygen levels"	Good water quality	Maximize water quality

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Goal	Goal Classification	Placement in Objectives Hierarchy
"Keeps harmful algal blooms down"	Good water quality	Maximize water quality
"Prevents Bay-wide eutrophication"	Good water quality	Maximize water quality
"Protects San Francisco Bay's beneficial uses"	Good water quality/wildlife habitat	Maximize water quality/Maximize wetland habitat
"Good wildlife habitat"	Wildlife habitat	Maximize wetland habitat
"Enhances wetland species richness and diversity"	Wildlife habitat	Maximize wetland habitat
"Done in a way to improve habitat use and ecosystem function of wetlands"	Wildlife habitat	Maximize wetland habitat
"Recovers endangered species"	Wildlife habitat	Maximize wetland habitat
"No effects on fish and wildlife"	Wildlife habitat	Maximize wetland habitat
"Removes other wastewater-derived contaminants"	Improve wastewater treatment	Maximize removal of chemicals of emerging concern
"Increases the water supply"	Improve wastewater treatment	Increase potable water supply
"Maximize water recycling to reduce nutrient loading"	Improve wastewater treatment	Increase potable water supply
"Recover resources from wastewater, like nitrogen, phosphorous, or energy"	Improve wastewater treatment	Increase resource recovery
"Having beneficial reuse [...] especially with drought and water demands, [increasing water recycling] is probably the biggest impact and biggest positive we could have"	Improve wastewater treatment	Increase potable water supply
"Not just wait and just use existing technology, but to test and help renew it"	Improve wastewater treatment	Addressed in MCDA option choice
"Actually capture [nitrogen] and use it as a resource"	Improve wastewater treatment	Increase resource recovery
"Increases climate resilience"	Climate concerns	Resilience to sea level rise
"Addresses sea level rise"	Climate concerns	Resilience to sea level rise
"Any facility upgrades should account for sea level rise"	Climate concerns	Resilience to sea level rise
"Minimizes greenhouse gas emissions"	Climate concerns	Minimize CO ₂ emissions
"Avoids unnecessary energy use"	Climate concerns	Minimize CO ₂ emissions
"Less energy-intensive"	Climate concerns	Minimize CO ₂ emissions
"Making sure this is part of strategy development for sea level rise"	Climate concerns	Resilience to sea level rise
"Complies with regulation"	Getting permits	Ease of permitting

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Goal	Goal Classification	Placement in Objectives Hierarchy
"Regulation should be phased in over time"	Getting permits	Ease of permitting
"Collaborative process across professional fields and regionally"	Collaborative process	Outside the scope of objectives hierarchy
"Collaborative process without litigation"	Collaborative process	Outside the scope of objectives hierarchy
"Do this with no attorneys. Meaning we maintain an actual collaborative all the way through, and everyone is giving and taking"	Collaborative process	Outside the scope of objectives hierarchy
"Regional cooperation"	Collaborative process	Outside the scope of objectives hierarchy

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Table S3. Supporting quotations for objectives, based on interviews with 32 stakeholders. Stakeholder number is given in parentheses in third column.

Objective	Quotation	Stakeholder Professional Role
Beautiful Bay and shoreline access	[Improved shoreline access to beautiful parts of the Bay shore is important] “so when we’re out explaining to our ratepayers why the rates need to go up [to control nutrient loads] it makes some sense.”	Wastewater treatment plant manager (SH7)
	“At the local level, [it’s important to have] a sense that the community is receiving the benefits of the investment. It gets very hard, for example, for a community to invest and not have it be something visible or tangible.”	Federal regulator (SH12)
	“Our [current wastewater infrastructure] is all out of sight, out of mind. That’s one of our challenges when we try to get people to support [wastewater infrastructure improvements], they’re like, “support what? Isn’t it all being taken care of?” I understand bringing that physical, human nature [of shoreline access] to understanding it. [...] It’s a factor from my perspective.”	Local regulator (SH4)
Ease of permitting	“If there’s a way to minimize either the amount of time or the amount of money it takes to get a permit, or if there’s some assurances from one permit to the next, [it would improve the appeal of a nutrient management option] [...] There’s real financial and resource implications.”	Wastewater treatment plant manager (SH7)
Flexible system adaptation	“How nimble could a [nutrient] management plan be, a plan of action be, if we saw an indicator [of bad ecological effects]? Because if we have to wait ten years to meaningfully change [nutrient] loading, that will likely be too late.”	Local regulator (SH4)
	[Good nutrient management should have an] “ability to upgrade nutrient removal from a low level of reduction to a higher level of reduction without sunk costs.”	Local regulator (SH16)
Increase useable water supply	“Are agencies taking advantage and creating synergies with water recycling during these upgrades?”	Wastewater treatment plant manager (SH22)
	“Having [nutrient control that includes] beneficial [water] reuse is probably my number one goal...If you just do a process [for nutrient control] and it doesn’t have any beneficial impact, then why are we doing it? To me, that’s the number one thing. There should be a beneficial impact. [...] Especially with drought and water demands, [water reuse is] probably the biggest impact and biggest positive we could have.”	Wastewater treatment plant manager (SH32)
	“If we’re good at saving water and recycling it for productive uses we may both augment our water supply and reduce the need to discharge those pollutants into the Bay and its tributaries. So I think those different kinds of more holistic looks at these things are critical to an effective strategy.”	Federal regulator (SH9)
	“Any solution implemented [for nutrient control] should achieve multiple benefits. And you know, in California’s current state of drought and sort of the main threat that is climate change, I think reducing our reliance on imported water should be a big priority. And probably through recycled water.”	Water quality advocate (SH8)
	“Are agencies looking at cost-effective capture of nutrients, instead of removal of nutrients? To put nutrients back into the agricultural stream.”	Wastewater treatment plant manager (SH22)
Increase resource recovery	[It’s important to] “look at nutrients not as a problem but as a resource. Actually [considering] nutrients in wastewater as a	Federal regulator (SH5)

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Objective	Quotation	Stakeholder Professional Role
	resource, and to see that it presents opportunities for increased energy recovery, [and] resource recovery for things that can be repackaged and used."	
Remove contaminants of emerging concern	"There are other water quality drivers in the Bay Area that are of concern... Some other emerging contaminants. Endocrine disruptors, and things like that which might conceivably be of concern. And so it's going to be important in looking at future infrastructure needs to consider not just a driver like nutrients and nutrient effects, but to see how does that fit with these other pollutant concerns? To sort of try to figure out [...] because you're only going to upgrade a wastewater treatment plant once every so often. You're not going to keep adding little widgets to wastewater treatment plants."	Federal regulator (SH5)
	"It's not just nutrients, right? You can remove heavy metals, you can remove pesticides, you can remove all of the chemicals and drugs, and pharmaceuticals, personal care products. So it's removing from the waste stream lots of different things. [...] It's not just for the nutrients. Now you've got five or six different priority issues that represent a longer-term need, that focus on our wastewater treatment plants."	Federal scientist (SH24)
Maximize water quality in the Bay	"The ultimate goal is to protect the Bay."	Wastewater engineer (SH23)
	"Our goal would be to be sure our discharge isn't creating a nutrient problem in the Bay."	Wastewater treatment plant manager (SH2)
Maximize wetland habitat	"[Nutrient management] also needs to very much think about longer and larger solutions that ideally would go above and beyond really any water quality threshold. What we tend to do nowadays [...] is as a society we tend to protect the environment just to that point where we're protecting an endangered species, or a bright-line threshold that we know has an impact. But we tend not to go to the extra work to really do the work properly to have a healthy, functioning, non-impacted ecosystem."	Federal scientist (SH25)
	[Nutrient management should be] "done in a way to improve habitat use of and ecosystem function of, for example, wetlands."	Local regulator (SH5)
	[Everyone should be] "taking advantage [of planning for nutrient control] to look at things like shoreline resiliency and wetland restoration as part of these upgrades."	Wastewater treatment plant manager (SH22)
Minimize greenhouse gas emissions	[Good nutrient management should] "avoid unnecessary construction and energy use."	Local regulator (SH10)
	[Good nutrient management should] "minimize energy usage and greenhouse gases."	Local regulator (SH16)
	[It is essential for good nutrient management to] "do no harm – [cause] no significant increase in greenhouse gas emissions."	Manager at a wastewater utility (SH19)
Minimize costs	"What are the highest value stabilization strategies per dollar spent? I think that's probably the greatest challenge."	Manager at a wastewater utility (SH21)
	"What might be expected out of improving treatment at some of the wastewater treatment plants [to control nutrients] could be very costly, and probably not cost-benefit."	Federal regulator (SH5)

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Objective	Quotation	Stakeholder Professional Role
	"The more those costs come down, the better able communities can afford it, obviously—so that means we [should] implement [nutrient control] in a way that doesn't overburden our society with costs."	Drinking water utility manager (SH15)
	"We want a bang for every billion dollars spent."	Local regulator (SH4)
Resilience to sea level rise	"There are issues related to sea-level rise that we need to think about when we figure out what our 21 st century wastewater treatment plant looks like."	Federal regulator (SH5)
	"With sea-level rise coming we know that a lot of our wastewater treatment plants that are down on the flats are going to either need to be protected or moved. So [nutrient management] might fit into a larger overarching opportunity to get the San Francisco Bay on a few larger regional wastewater treatment plants that do a much better job—but up and out of the Baylands so that they don't have to have seawalls around them [...] move them up and out well above high water marks you expect in 50 to 100 years."	Federal scientist (SH25)
Technical reliability	[It is essential that good nutrient management options] "are reliable, and can decently meet our treatment requirements [...] Because we want to make sure that we're consistently meeting our goals."	Wastewater treatment plant manager (SH7)
	"We want to make sure that when we're investing in big capital dollars [for nutrient control], that the technology is proven. It's going to work. It can be operated by operators reliably."	Wastewater utility advocate (SH1)

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Table S4. Supporting quotations from stakeholders about barriers to multi-benefit water infrastructure projects. Stakeholder number is given in parentheses in the final column.

Category	Barrier	Supporting Quotation	Stakeholder Professional Role
Institutional	Leadership	“What organization or agency would be the one to deal with an issue [of multi-benefit infrastructure for nutrient control] like that?”	Baylands steward (SH6)
		“Who is managing it [multi-benefit infrastructure for nutrient control]? And who is making the wise decisions? And who is resolving the natural disputes that are going to arise?”	Wastewater treatment plant manager (SH3)
		“What’s your overriding goal?”	Wastewater treatment plant manager (SH3)
	Collaboration	“In our case, [water recycling for nutrient control] involves another agency. And I don’t know how water recycling fits into [the water supply agency’s] long-term supply strategy.”	Wastewater treatment plant manager (SH7)
		[Multi-benefit nutrient control] “would also depend on relationships with other entities-- like water supply district, or planning agencies, or the community and their receptiveness.”	Wastewater utility manager (SH2)
	Permitting	“If [nutrient control] has multi-attributes, it’s going to be harder [to permit] ... It’s when you try to meet multiple goals, then it gets harder.”	Wastewater discharge manager (SH2)
		“In those new discharge scenarios: the unconventional stuff, where you say rather than discharge waste to the Bay, discharge to wetlands -- that does have some permitting challenges. I don’t want to downplay that.”	Local regulator (SH13)
	Risk tolerance	“Using something like wetlands or horizontal levees to try to treat nutrients? It may have some promise in the future, but I don’t think anyone right now, including the regulators, would say this is the way to go. Because they don’t know what the outcome is going to be or if there’s going to be other challenges. Solve one problem, create two more down the road sort of thing.”	Wastewater treatment plant manager (SH7)
		“There’s a lot of aversion in the industry to new stuff. Until they’ve seen it happen – they’re used to this high degree of reliability. It’s almost unrealistically high. A lot of it has been driven by compliance considerations and enforcement.”	Local regulator (SH4)

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Category	Barrier	Supporting Quotation	Stakeholder Professional Role
Social	Public opinion	"[Urine source separation and treatment] sounds insane. Just insane!"	Wastewater treatment plant manager (SH3)
		[People can adapt to urine source separation.] "Think about how we've adapted as humans. [Consider] seatbelts [...] I was from a generation when you never used a seatbelt. The concept of a seatbelt was like, what? You've got to be kidding. It took me a while, but then you adapted and now you just do it."	Local regulator (SH4)
		"If you're going to depend on the public to actually do something [for nutrient control] – I don't think that's a good strategy."	Baylands steward (SH5)
	Public compliance	"It's hard enough to get people to recycle – so getting them to carry their urine in a bottle [...] unless it was double piped and that would be really expensive."	Federal regulator (SH9)
		"We have a hard-enough time getting people to separate their food scraps [for compost], much less their pee from their poo."	Wastewater advocate (SH1)
Technical	Effects on existing treatment	"They want you to recycle more, but by recycling, they're removing the water that keeps my effluent diluted enough that I might possibly, barely meet the selenium and mercury regulations. That will be the repercussions of what they're doing. There will come a point where we'll be in constant violation unless we shut off the recycling things. If they do [more water recycling], I'm not sure I can meet the ridiculously low limits."	Wastewater treatment plant manager (SH3)

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Table S5. Supporting quotations for strategies to overcome barriers to multi-benefit infrastructure. The stakeholder number is given in parentheses in the final column.

Category	Barrier	Strategies to Overcome barriers	Supporting Quotation	Stakeholder Professional Role
Institutional	Collaboration	Establish networking relationships between different agencies, organizations and water managers <i>before</i> decisions need to be made	“Fortunately, over the years there’s been a more cooperative environment that’s built up in the Bay Area anyway, in terms of water quality planning [...] There has been a long-term cooperative monitoring program for San Francisco Bay into which a lot of the dischargers sort of pay into this rather than running their own monitoring programs. And I think there’s been good experience with that, and that has led people to maybe be a little more open to this kind of approach [multi-benefit wastewater infrastructure].”	Federal regulator (SH9)
			“When you have, for example, the annual meetings of the RMP [Regional Monitoring Program], and you talk about data -- Having that group of scientists, and regulators, and dischargers, and NGOs have meaningful discussion around that data and what it means, and the fact that it requires something to be done, is a powerful way to have a foundation for doing something [with multiple benefits].”	Federal regulator (SH16)
		Structure permits regionally to force interaction and collaboration between dischargers	“Traditionally, we tend to look at wastewater permits sort of facility by facility. And oftentimes we do not do a great job looking at how they operate as a collective, in looking at their collective impacts – but also looking at them as a group of associated operations that might have the capacity to cooperate in doing work to address a problem of concern.”	Federal regulator (SH9)
		Regulators, dischargers, and technology developers/scientists collaborate to develop regulations that support adoption of innovative technologies	“We don’t want to wait and just be regulated towards the existing technology. We’re looking for new [multi-benefit] technology.”	Wastewater treatment plant manager (SH28)

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Category	Barrier	Strategies to Overcome barriers	Supporting Quotation	Stakeholder Professional Role
	Permitting	Increased permit length	“Five years would be unreasonable [to plan and implement a multi-benefit wastewater infrastructure project], for sure. Just because of the money involved, and the time it takes to go through all of the items I just discussed [different alternatives, technologies, costs, and environmental review]. A more reasonable timeframe would probably be something along the 10- to 15-year range.”	Wastewater treatment plant manager (SH2)
			“If there’s a way to minimize either the amount of time or the amount of money it takes to get a permit [for a multi-benefit infrastructure project], or if there’s some assurances from one permit to the next, because the target’s always moving. Having a longer permit, having a 10 or 15-year permit, would make the process feel a little less painful, because you’re making the investment for a longer period of time.”	Wastewater treatment plant manager (SH7)
	Costs	Increased institutional funding for research	“Our public agencies are not set up as research institutions--and most of us don’t collect any dollars for research. [...] Maybe we should. Why wouldn’t we be, just as in the private side--if you want to grow your business or you want to expand that, you have to spend money on research and development? We just don’t do that as public sector. And it sorely is needed.”	Wastewater treatment plant manager (SH28)
		Find ways to share costs	“[We need to] find a way to incentivize [multi-benefit infrastructure] through a cost-share program to say ‘If we made this change, it would benefit you, but it would also benefit nutrient discharge.’ You know, find a source of funding to offset those improvements or cost share. You can kind of get more progress with carrots than you can with a stick.”	Baylands steward (SH25)
	Risk tolerance	Develop easily implemented and adaptable technologies	“Given that implementation of change in wastewater treatment is 5-10 years, are there things that could be implemented quicker, that are not full upgrades? Are there	Regional regulator (SH4)

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Category	Barrier	Strategies to Overcome barriers	Supporting Quotation	Stakeholder Professional Role
			things that are readily available, when we need change, that could kick in? [...] That's why I'm getting some interest in new technologies. Maybe are they quicker to implement than the full upgrade? [...] Rather than having a risk-aversion based approach [build proven traditional nutrient removal upgrades at wastewater treatment plants] that could be very costly, we're going to accept some risk [and try to implement unproven technologies], as long as we can adapt reasonably quickly."	
Social	Public opinion	Make wastewater treatment more visible	"I was very much moved by [...] how the Roman system was built with these public fountains, and it was reasonably well funded relative to the economy, and a big part of it was people knew what it was all about. Versus our [wastewater infra-] structure is all out of sight, out of mind. That's one of our challenges when we try to get people to support stuff [like multi-benefit wastewater infrastructure], they're like, "support what? Isn't it all being taken care of?"	Regional regulator (SH4)