Implications of Climate Change for Adaptation by Wastewater and Stormwater Agencies

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ABSTRACT

Climate changes produced by warming may result in *impacts* on hydrologic and environmental processes that may have *implications* for wastewater and stormwater facilities and operations. The uncertainty in climate forecasts is magnified many times by the complexities of tracing climate effects through the subsequent hydrologic and environmental processes that may produce changed operating conditions confronting wastewater and stormwater agencies. This paper illustrates a risk management approach to managing the impacts and implications of climate change in the face of these uncertainties.

KEYWORDS: climate change, global warming, vulnerability assessment, adaptation, wastewater, stormwater, risk management, sustainability.

INTRODUCTION

In the last several years, global warming has become more generally accepted. The “Greenhouse Effect” (in part, attributable to increased levels of CO_2 from our energy use) will continue to worsen over the next several decades and for a period of centuries even if we act aggressively right now to restrain our contribution to the problem.

This sustained increase in temperatures will change our climate in a number of ways. The changes set in motion by higher temperatures are interrelated with one another in very complex ways. So, the net impacts will include not only direct changes in climate variables, but also secondary changes manifest through the altered behavior of related Earth systems such as the hydrologic cycle, the oceans, ice sheets, geochemical processes and terrestrial and aquatic biota and ecosystems.

The linkage between the rate of temperature rise and the timing and location of these more complex secondary effects on Earth systems is where the science is most challenged and the uncertainties are greatest. Changes presenting significant issues for wastewater and stormwater facilities and operations could already be happening or could be decades away. Many effects may be expected to advance gradually as a function of gradual temperature rise, and yet the same phenomena may be subject to stochastic influences that could produce extreme events much sooner than implied by the gradual trend.

Climate change presents a much greater degree of uncertainty than is typically encountered in facilities and operations planning. How do you prepare for changes of unknown magnitude on an unknown timeline? There is a great temptation to wait and see if climate science can be improved to provide a better basis for action. But, it would be a mistake to just ignore climate change and resume a business as usual approach to planning. Since it is certain that climate is changing, planning that is based on the assumption of "stationarity" (known climatic variability) is certain to be flawed. Moreover, uncertainties affecting the local conditions that matter most to wastewater and stormwater agencies are not likely to be greatly reduced by further scientific study of global climatic processes. The uncertainty in climate forecasts is magnified many times by the complexities of tracing climate effects through the subsequent hydrologic and environmental processes that produce the changed operating conditions that wastewater and stormwater agencies will have to face.

Early in 2010, the authors produced a report for the Water Environment Research Foundation (WERF, 2010) that offers a way to move forward through a risk management approach. Most of this paper is abstracted from the report which is available on the WERF web site (see References). The familiar risk management paradigm consists of three steps: 1) risk identification, 2) risk assessment/characterization, and 3) risk management. The application to climate change adaptation planning is quite unique. It is necessary to first take the problem apart and examine it piece by piece to perform a thorough risk identification analysis. The possible impacts of increasing temperatures are far reaching when all the secondary effects on hydrologic and environmental processes are taken into account. This "deconstruction" of the problem is accomplished with the aid of a number of cause-effect impact tree diagrams that are reproduced in this paper. They provide a good overview of the full scope of the problem and a handy means of organizing information about it.

The cause-effect impact tree diagrams represent four major chains of causation that may be expected to result from global warming (see Figure 1). First, as temperatures rise, it is expected that sea levels will rise due to warmer ocean temperatures and melting of land ice such as glaciers. Next, warmer overall temperatures are expected to produce two important changes in seasonal conditions over most of the continental United States. Warmer and shorter winters are expected. And, warmer and drier summers are expected in most of North America. Lastly, warming is expected to accelerate and amplify the functioning of the hydrologic cycle to produce, among other things, more intense rainfall events. The cause-effect impact tree diagrams trace through the linkages to show how *climate changes* produced by warming may result in *impacts* on hydrologic and environmental processes that may have *implications* for wastewater and stormwater facilities and operations.

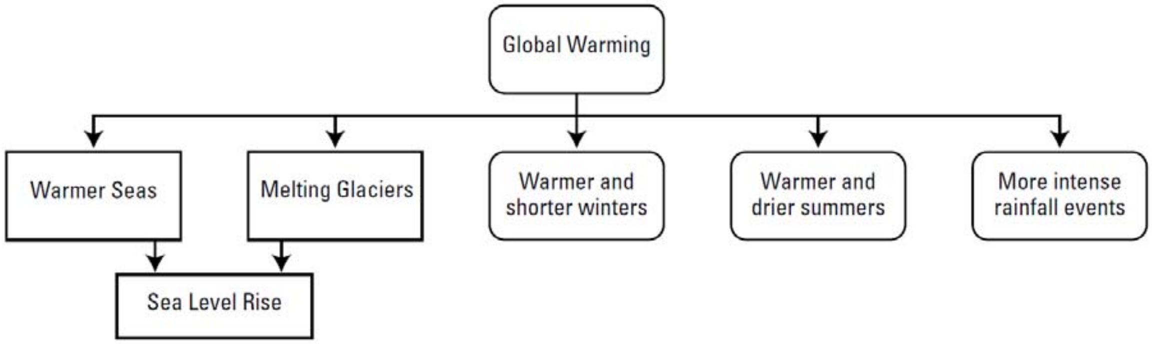


Figure 1. Major categories of impacts from global warming (WERF, 2010).

It is important to stress that while these cause-effect impact tree diagrams provide an intuitive and structured approach to risk identification, these are only *potential* risks. The magnitude and timing of these potential downstream effects of global warming remains highly uncertain, as discussed above. A risk characterization step needs to be undertaken to assess what is known and what is not known about the possible magnitude and timing of these *potential* impacts and implications along each of the branches. To assist in making that risk assessment, the above referenced WERF report provide a background review of the current understanding of climate change at a global level, including forecasts for the continental United States.

This paper illustrates a risk management approach to managing the impacts and implications of climate change through “reconstruction” of the information provided in the cause-effect tree diagrams – bundling individual threats together for analysis in terms of common endpoints relating to major facilities and operations. For example, the cause-effect impact tree diagrams identify a large number of *potential* impacts spawned by global warming that could affect performance requirements for wastewater treatment plants. But these multiple threats are driven by different processes that are understood with varying levels of confidence and are proceeding on differing timelines. From a risk management perspective, it is therefore necessary to evaluate each such “threat bundle” as a package to assess which specific causative influences are likely to be critical for short-term versus long-term decisions, and to assess adaptation options with a composite rather than a piecemeal approach.

RISK IDENTIFICATION

The inherent complexity of climate change and the related information overload can be a barrier to engaging in adaptation planning. There is a growing amount of information about climate change. Some presentations are piecemeal and others are overwhelmingly technical. There are many interrelated aspects relating causes and effects; there is a crucial time dimension; and there are large uncertainties that will likely not be resolved in the near term. These complications need to be surmounted to progress into an action phase involving adaptive responses.

One prevalent obstacle arises from the fact that it takes many words and figures and tables to describe the potential cascading impacts of a warming climate. It takes even more to assess the possible timing and magnitude of all these effects. The cause-effect impact tree diagrams displayed in the next several pages (Figures 2 through 9) are intended to combat this information overload by presenting the total picture in a compact form. The cause-effect logic of the diagrams also provides a useful framework for bundling or categorizing the numerous potential impacts in terms of the four different chain reactions set loose by global warming: sea level rise, warmer and shorter winters, warmer and drier summers, and more intense rainfall events. The second half of this paper illustrates how a risk management approach can be applied to each of them.

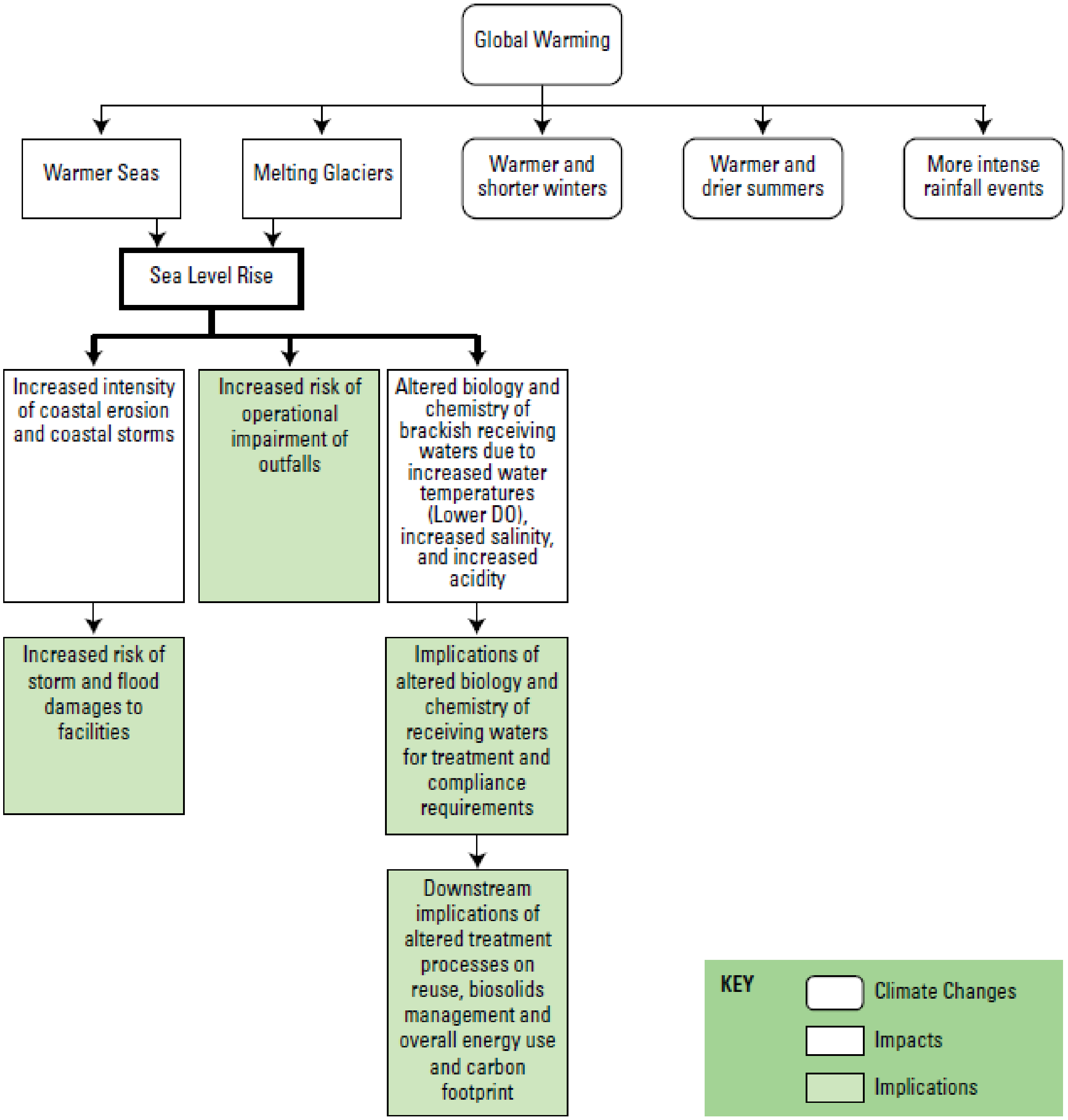


Figure 2. Impacts and Implications of Sea Level Rise for Wastewater Agencies (WERF, 2010)

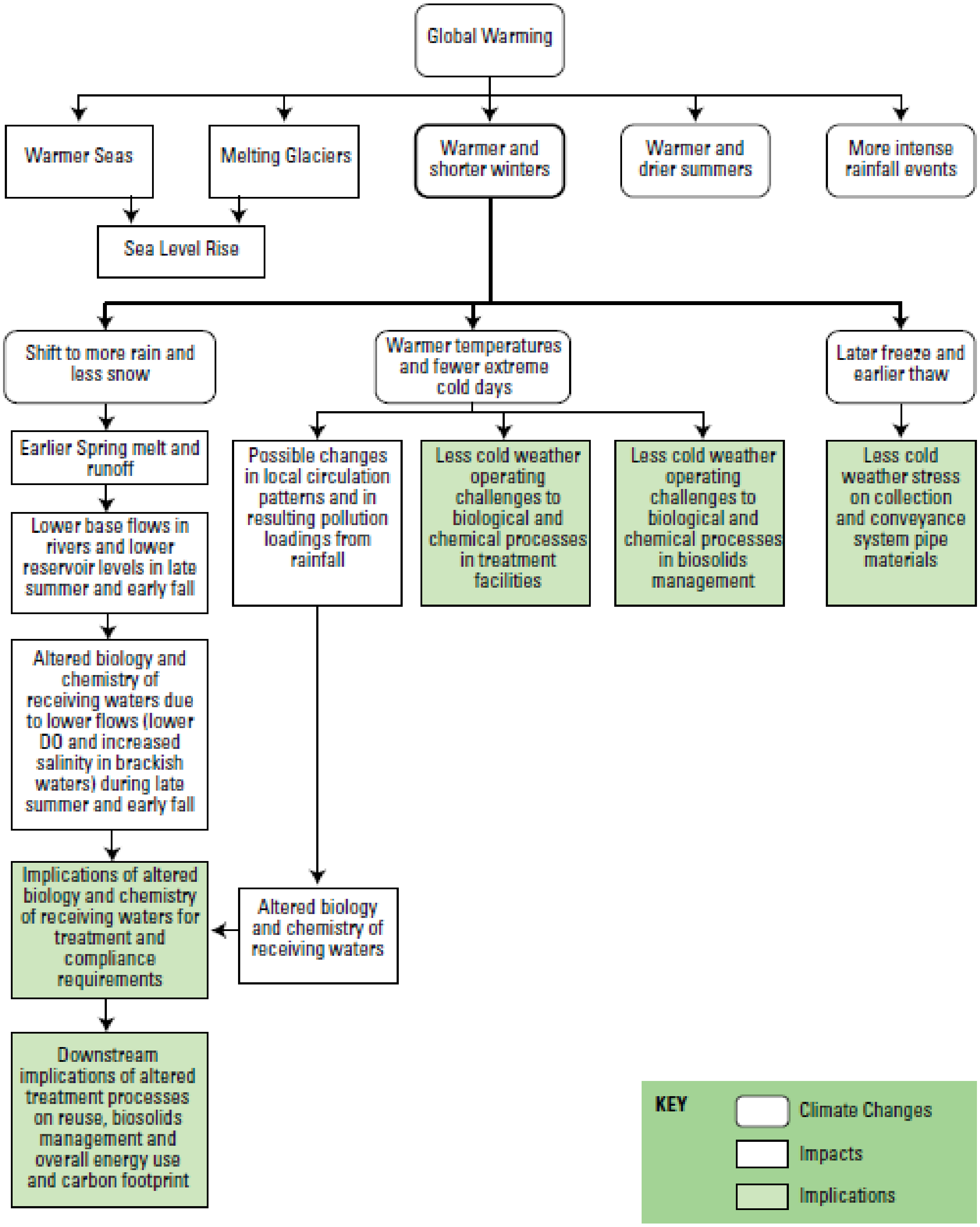


Figure 3. Impacts and implications of warmer and shorter winters for wastewater agencies (WERF, 2010).

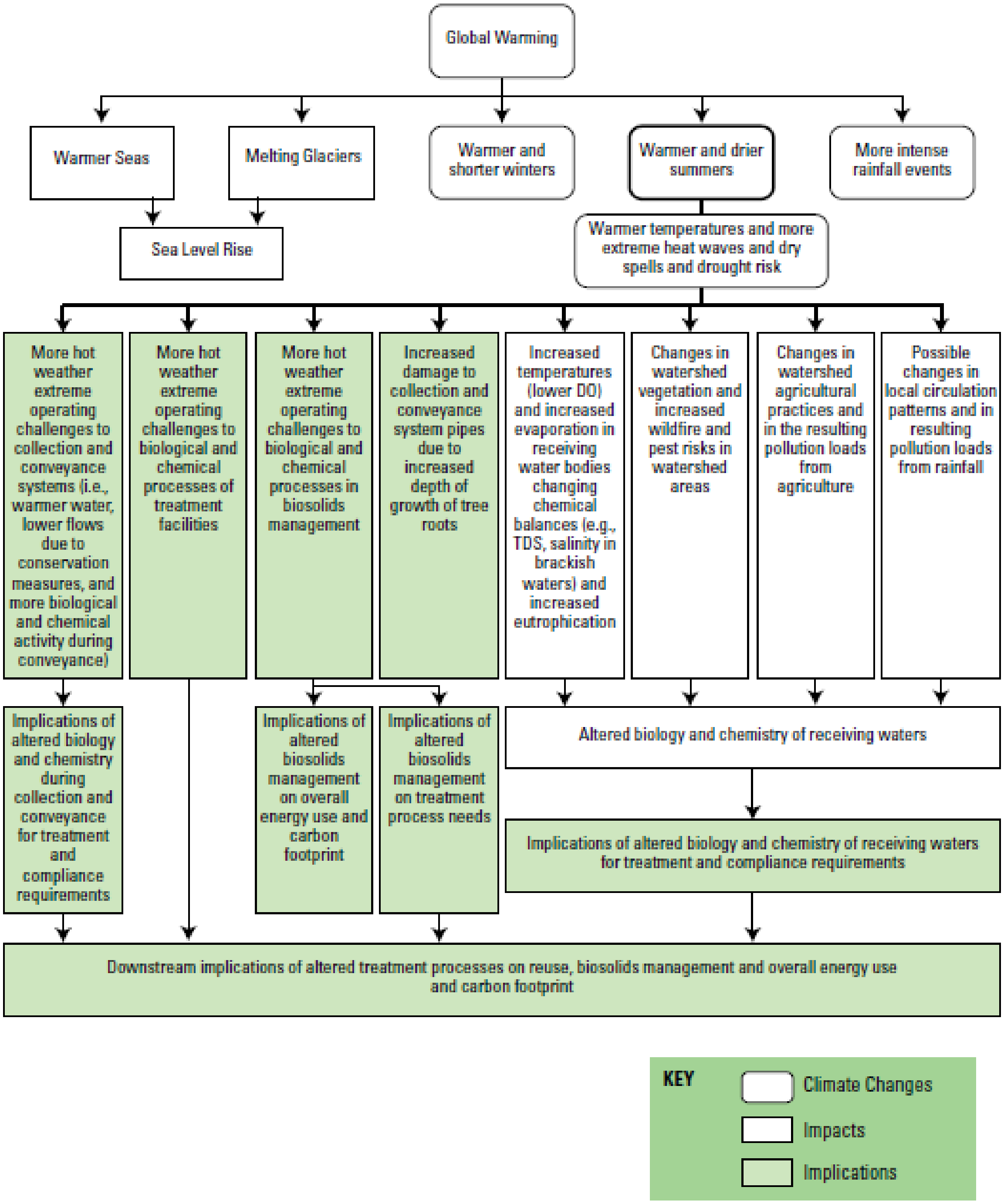


Figure 4. Impacts and implications of warmer and drier summers for wastewater agencies (WERF, 2010).

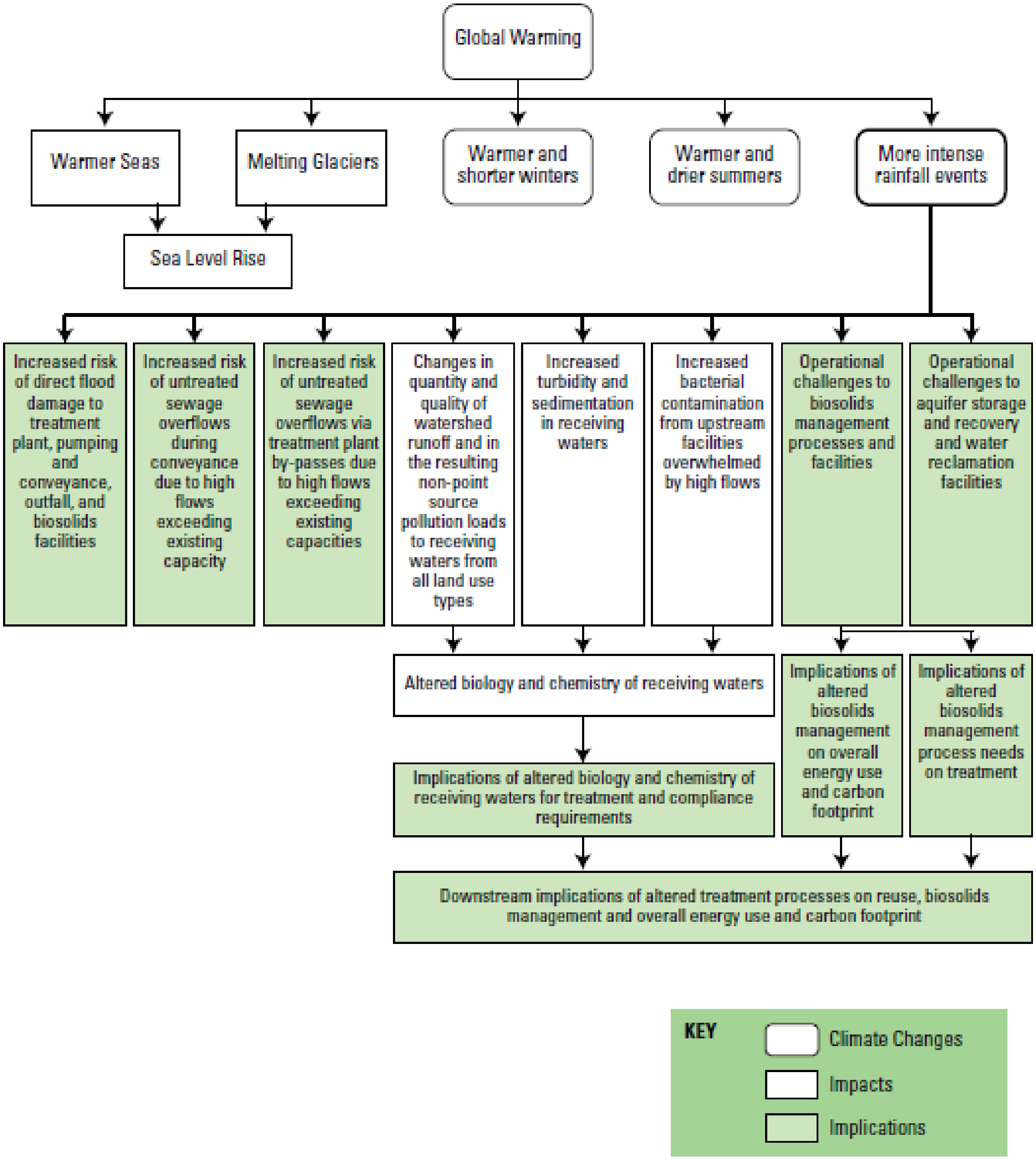


Figure 5. Impacts and implications of more intense rainfall events for wastewater agencies (WERF, 2010).

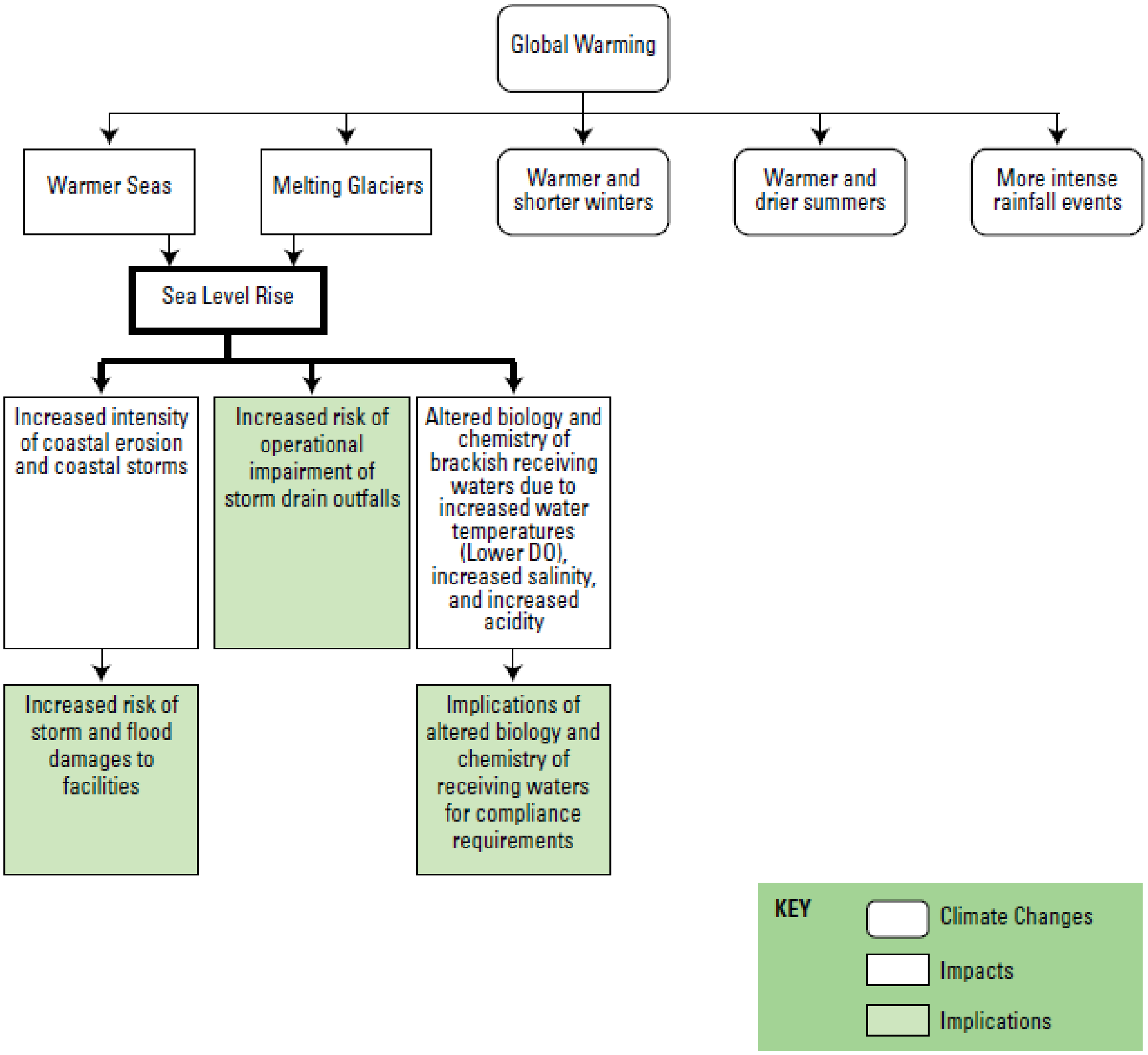


Figure 6. Impacts and implications of sea level rise for stormwater agencies (WERF, 2010).

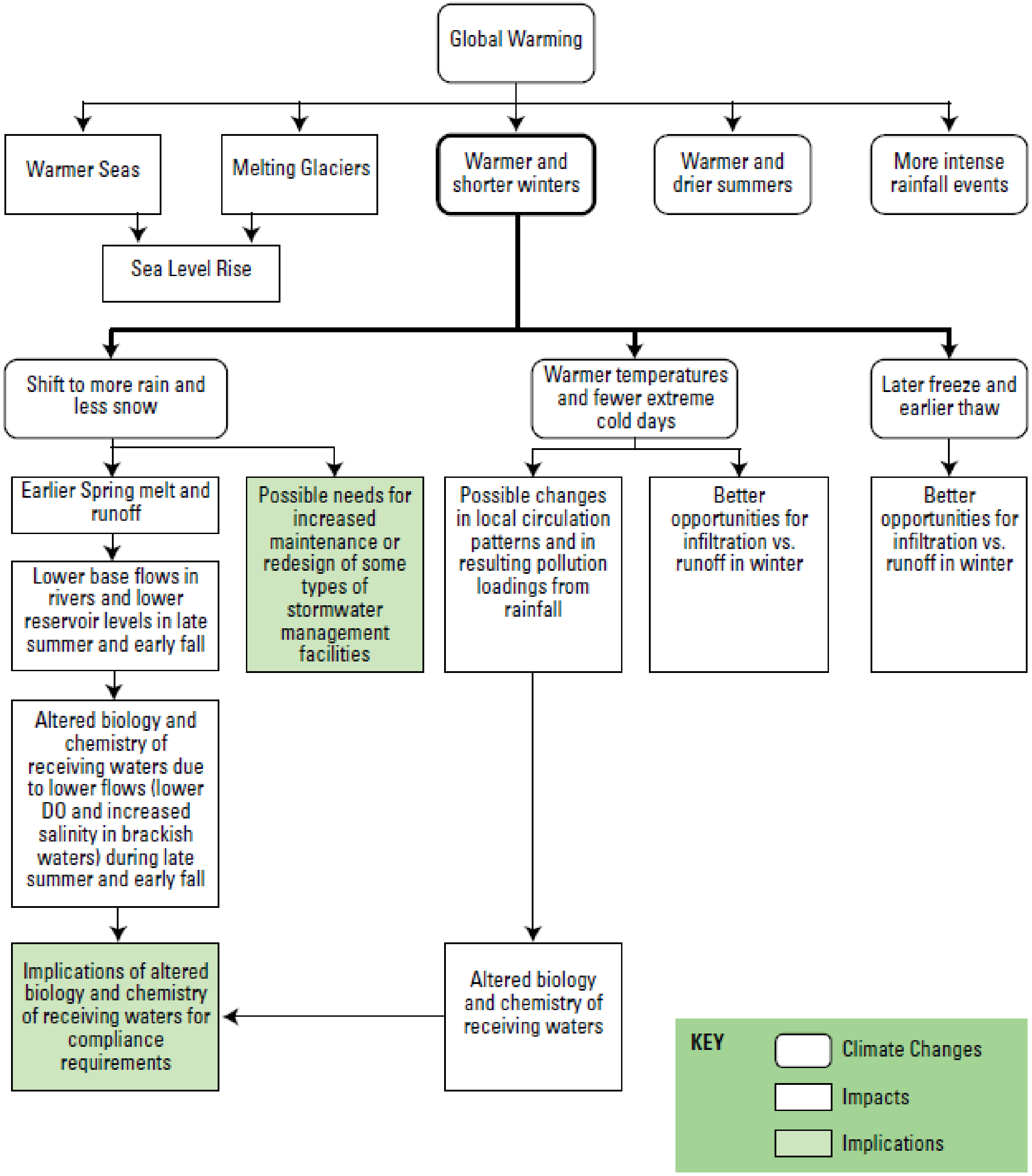


Figure 7. Impacts and implications of warmer and shorter winters for stormwater agencies (WERF, 2010).

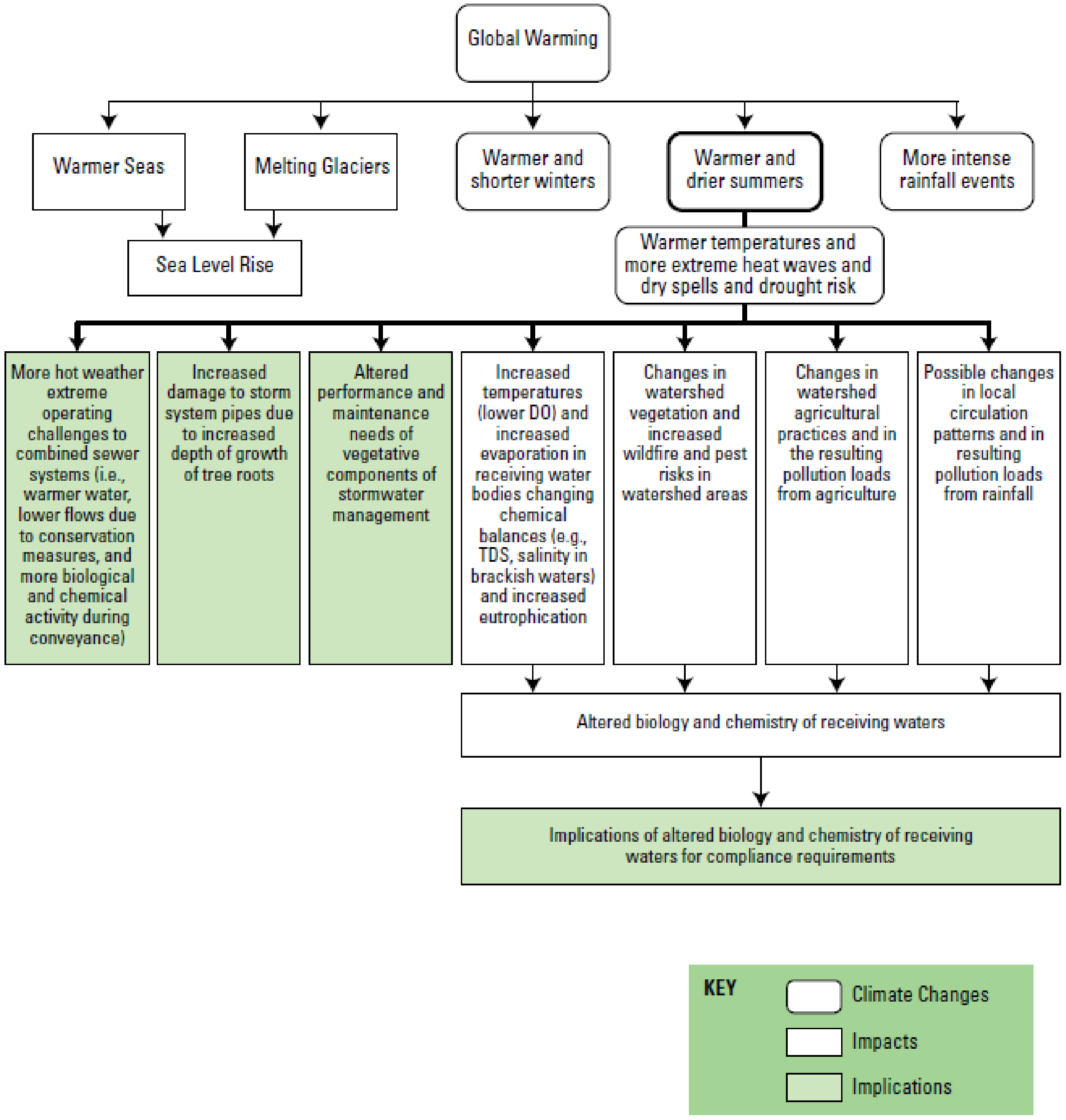


Figure 8. Impacts and implications of warmer and drier summers for stormwater agencies (WERF, 2010).

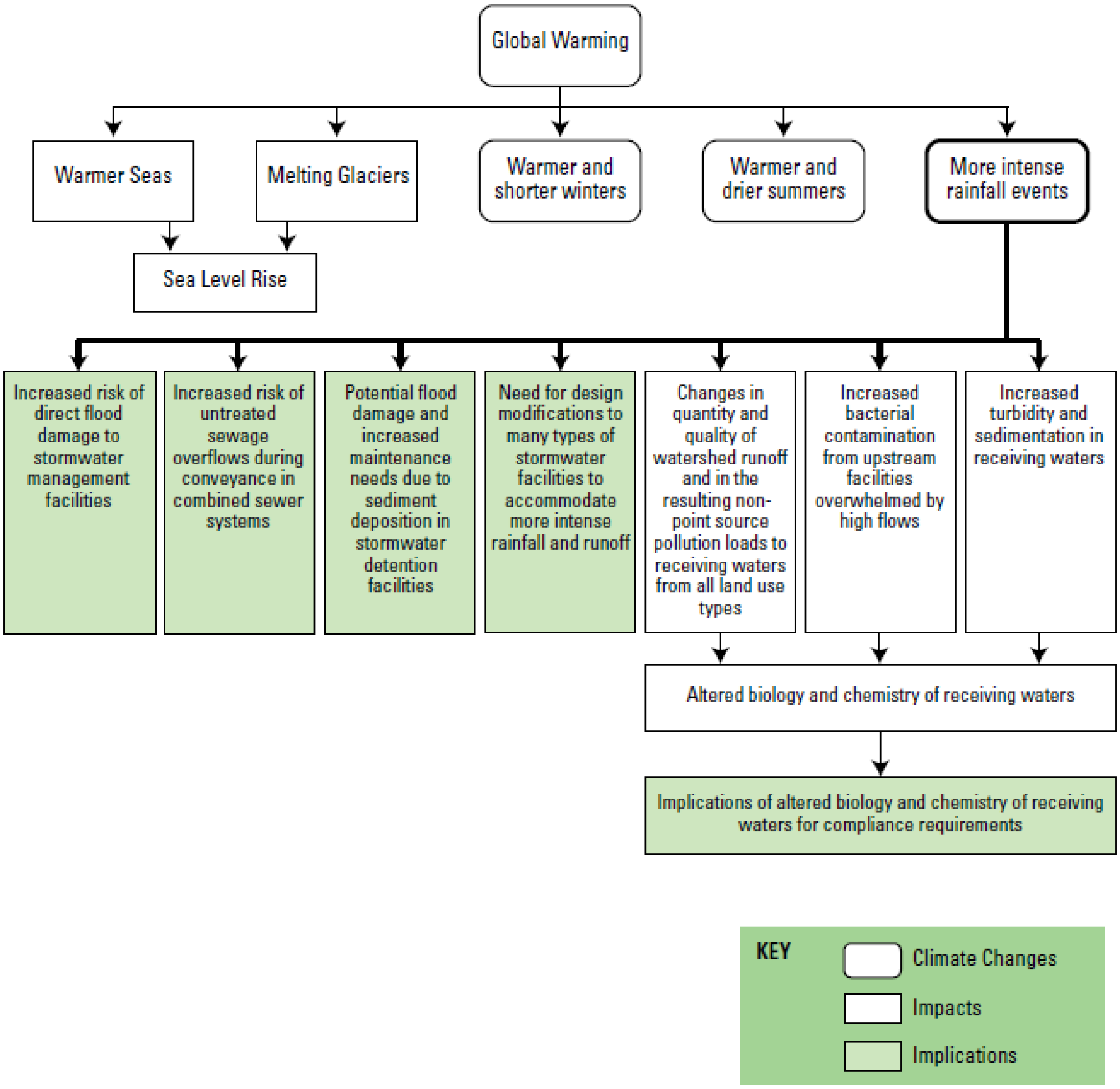
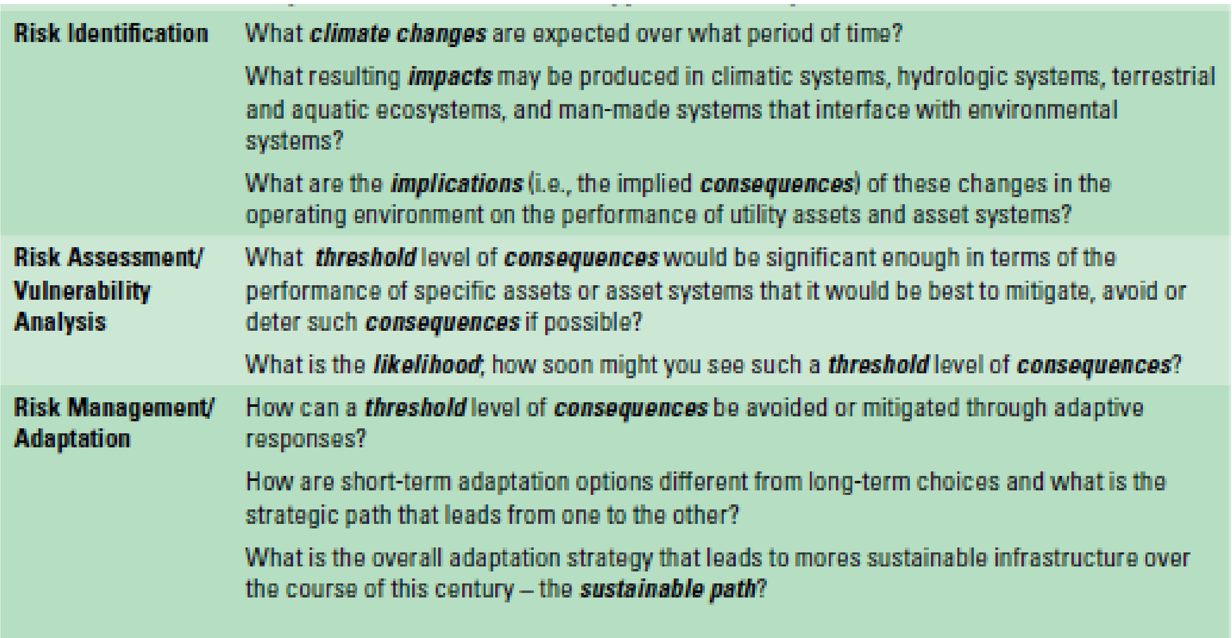


Figure 9. Impacts and implications of more intense rainfall events for stormwater agencies (WERF, 2010).

RISK MANAGEMENT

Risk Management Approach to Adaptation Planning

The risk identification step in analyzing climate change is a straightforward exercise. Basic climatic, hydrologic and ecologic principles can be followed to trace the path from climate changes to potential impacts on facilities and operations, as illustrated in the preceding cause-effect diagrams. The next steps in the risk management paradigm are risk assessment (or characterization) and risk management (see Figure 10). In the climate change field, these are often referred to as vulnerability analysis and adaptation analysis.



Risk Identification	What ***climate changes*** are expected over what period of time?
	What resulting ***impacts*** may be produced in climatic systems, hydrologic systems, terrestrial and aquatic ecosystems, and man-made systems that interface with environmental systems?
	What are the ***implications*** (i.e., the implied ***consequences***) of these changes in the operating environment on the performance of utility assets and asset systems?
Risk Assessment/ Vulnerability Analysis	What ***threshold*** level of ***consequences*** would be significant enough in terms of the performance of specific assets or asset systems that it would be best to mitigate, avoid or deter such ***consequences*** if possible?
	What is the ***likelihood***; how soon might you see such a ***threshold*** level of ***consequences***?
Risk Management/ Adaptation	How can a ***threshold*** level of ***consequences*** be avoided or mitigated through adaptive responses?
	How are short-term adaptation options different from long-term choices and what is the strategic path that leads from one to the other?
	What is the overall adaptation strategy that leads to mores sustainable infrastructure over the course of this century – the ***sustainable path***?

Figure 10. Risk management approach to adaptation planning (WERF, 2010)

An essential aspect of applying these time-tested steps in risk management to climate change adaptation is the need for a critical awareness of the time dimension. The impacts and implications of climate change will emerge continually over the next several decades – and centuries. Moreover, they will emerge at differing rates and intensities that will be manifest through a number of direct and indirect mechanisms. Adaptation should not be viewed, therefore as taking individual steps to address discrete risks, but rather as a series of steps to be taken over time to cope with an array of ever-changing risks. Taken together, the successive steps will trace a pathway to the future. This highlights the need for a strategic element in adaptation. As climate change unfolds during the remainder of this century, a central question will be defining the *sustainable path* (Aspen Institute, 2009) that leads from the existing asset configuration to a new one that is *climate ready*.

Some risks may be perceived to be strong enough in the short term that wastewater and stormwater agencies should be already implementing adaptive measures, while other types of risks may be perceived to be so weak over the short term that they may not require significant changes in facilities or operations for decades. The prospect of climate change sometimes evokes a misperception that the sky is falling and leads people to skip right over the risk characterization step and begin evaluating adaptation options as though everything is happening at once. It is prudent to first undertake a vulnerability analysis to assess how soon the impacts may materialize at a strong enough level to present a meaningful threat to existing or planned facilities and operations. In cases where the change processes are initially weaker phenomena that will develop gradually, adaptation will become a long-term undertaking where the responsibility of current managers is limited to laying the right foundation to enable selection and implementation of the best adaptations by future generations of managers.

In devising adaptation strategies, it will be important to be mindful of the fact that today's risks are not the same as tomorrow's and today's assets are not the same as tomorrow's. Asset management maximizes the value derived from infrastructure by optimizing asset life cycles in terms of capital and O&M costs. Climate change presents a suite of new variables that may cause re-evaluation of the presumed remaining lives of existing assets. Decisions about the level of upgrade, rehabilitation, maintenance or replacement expenditures necessary to keep assets in service at desired levels of performance may vary depending on whether the remaining useful life of the asset is regarded as short or long – relative to the rate at which climate driven threats to the asset are believed to be advancing.

Climate change certainly involves some strong short-term threats to existing assets that will call for protective measures to *sustain* them. But, the current asset configuration may not be the *most sustainable* choice for the long-term. Future generations may need a different type of infrastructure that is designed from the start to be more sustainable in a changing environment, involving nontraditional types of investments such as decentralized treatment, green infrastructure, watershed buffers and wetlands.

However, asset management is often grounded in the assumption of a stationary climate in which the old asset is simply replaced by a new one. Asset management will have to be broadened to incorporate alternative concepts of infrastructure that may provide more value in a changing environment. In incorporating alternative infrastructure concepts, it is especially necessary to be sensitive to the potential for "path-dependency" in the sequencing of adaptation choices. In some instances, an incremental approach to adaptation might result in an inadvertent commitment to one path over another. For example, in a situation where the climate change signal is initially weak and developing slowly over the long-term, conventional infrastructure may continue to be selected because it continues to perform well in conditions that do not differ markedly from historical climate. But, it could be the case that an alternative infrastructure – perhaps a green infrastructure solution involving vegetation – is what is needed in the long-run. Since vegetation takes time to mature (especially trees), it may not be prudent to wait until the climate change signal is strong before selecting this path, better to use that time letting the trees grow.

In sum, the overall challenge in vulnerability assessment and adaptation is one of using risk management principles to help define the most *sustainable path* for infrastructure that will be best suited to a continually changing operating environment. This is summarized in the decision tree diagram in Figure 11.

Vulnerability Analysis (Risk Assessment/Characterization)

The level of uncertainty involved in predicting climate change impacts is much greater than that normally encountered in facility and operations planning. This degree of uncertainty may lead many to choose to ignore climate change in their planning. But that would be a mistake because climate is changing. One thing that we can say with certainty is that the future climate will not be the same as the past. This has generated the catch phrase: “stationarity is dead.”

But in the presence of such uncertainty, how is it possible to know how and when to adapt? The planning approach recommended in much of the climate adaptation literature is broadly referred to as a “bottom-up” analysis (or *threshold* approach). It relies on system managers’ knowledge of their operations. This is especially useful because there is a wide array of practical consequences of climate change that cannot be predicted by climate models. The best information the models provide is long term changes in mean climate. It may be that changes in extreme events over the next 20 years are far more important for planning now. The bottom-up approach to vulnerability analysis begins by asking a very practical question:

“What *threshold* level of change in the combination of climatic, hydrologic and environmental parameters would constitute a significant challenge – an unacceptable failure risk – to existing or planned facilities and operations?”

Working from the “bottom-up,” this approach is anchored in existing or planned facilities and operations with which there is good staff knowledge of performance characteristics and the tolerances of these systems to extreme operating conditions. A *threshold* level of challenge can be defined that would produce a level of failure in critical components or systems that is unacceptable. (Episodes of noncompliance with EPA regulations certainly qualify as threshold events, but the concept of climate-induced critical failures is also much broader.) This threshold determination can be accomplished on the basis of staff knowledge alone, without having to have a climatologist in the room at all. Clearly, avoiding this critical level of failure or mitigating the consequences of such failure should be a central objective of adaptation planning.

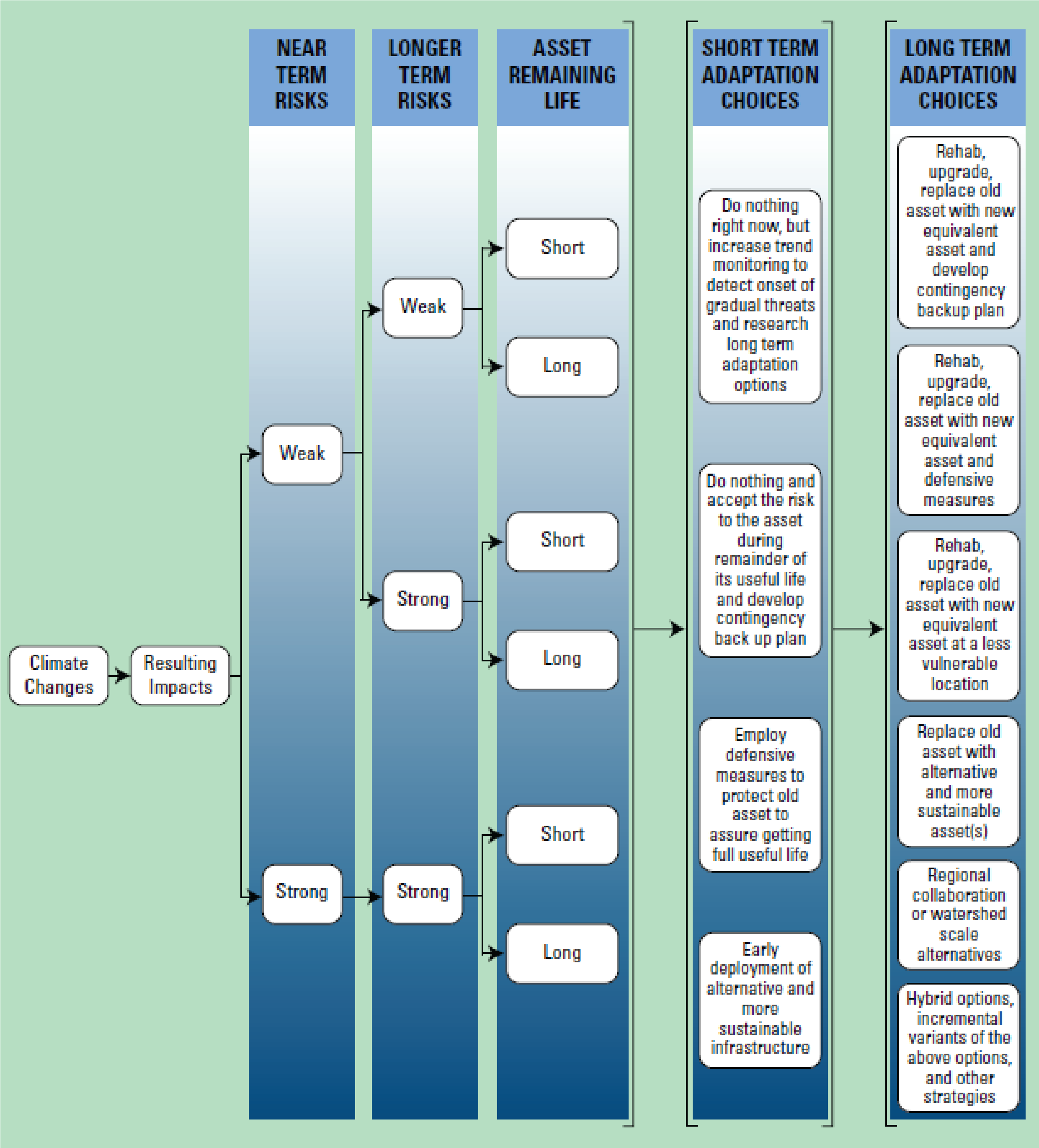


Figure 11. Finding the *sustainable path* in adaptation planning (WERF, 2010).

Once the potential risks to specific assets or asset systems are characterized in terms of a critical threshold, the next question in vulnerability analysis is the likelihood of such threshold events within planning horizons or other meaningful time frames:

“What is the likelihood of seeing a *threshold* level of change in the combination of climatic, hydrologic and environmental parameters that would constitute a significant challenge – an unacceptable failure risk – to existing or planned facilities and operations within capital planning or other meaningful time horizons?”

This is where climate change science needs to be drawn upon. Outputs from climate science need to be consulted to assess what is known about changes in climatic and environmental conditions that could produce situations that exceed the defined thresholds. Both the likelihood of occurrence and timing need to be addressed. Most answers will not be definitive. There are so many uncertainties about climate change that responsible scientists at best can identify ranges of changes, not make specific predictions.

Although this step can be daunting, it is not prudent to simply freeze planning decisions until better predictive tools become available. Developing better predictions of climatic changes as a first step in vulnerability analysis has been termed the “top-down” approach to vulnerability analysis in the climate literature. An overview assessment of the state of the art of the top down climate modeling tools has recently been completed by the Water Utility Climate Alliance (WUCA, 2009). While there is promise for somewhat better information, it will take considerable time to develop. Many adaptation decisions should be made sooner and the level of improvement possible in forecasting will still leave decision makers facing a much greater degree of uncertainty than what is customary under the conventional assumption of stationary (or, known) climatic variation.

Adaptation Analysis (Risk Management)

While assessing the likely timing of a *threshold* level of impact can be difficult, adaptation decisions might be made tractable by distinguishing between the short term and the long term responses to a given threat. It is logical to ask not only:

“How can the consequences of an anticipated *threshold* level of impact be avoided or mitigated through adaptive responses?” But also: “How are short term adaptation options different from longer term choices and what is the strategic path that leads from one to the other?”

In other words: What is the overall adaptation strategy that leads to more sustainable infrastructure over the course of this century – the *sustainable path*?

A popular rule of thumb encourages that the guiding principles of adaptation should be: flexibility, flexibility and flexibility. This has both short- and long-term connotations. Large, fixed capital commitments are more risky in a changing climate due to the increased uncertainties in the operating environment that may alter the planned useful life and lifecycle cost of such facilities and hence diminish the value derived. Moreover, capital is a limited resource. Placing big bets on what turns out to be the wrong infrastructure and leaving the next generation with large debts on the books might make it difficult to afford the right infrastructure later.

Staged implementation of smaller increments of capital additions has been suggested as a strategy for conserving capital and keeping options open to move in a different direction if climate change effects make it unfavorable to build additional increments. A caution has been raised, however, that due to the gradual nature of some of these change processes, incremental decision making can inadvertently lead down the path of building more conventional infrastructure grounded in assumptions of stationary climate when the path to building a more sustainable infrastructure may lie in a different direction.

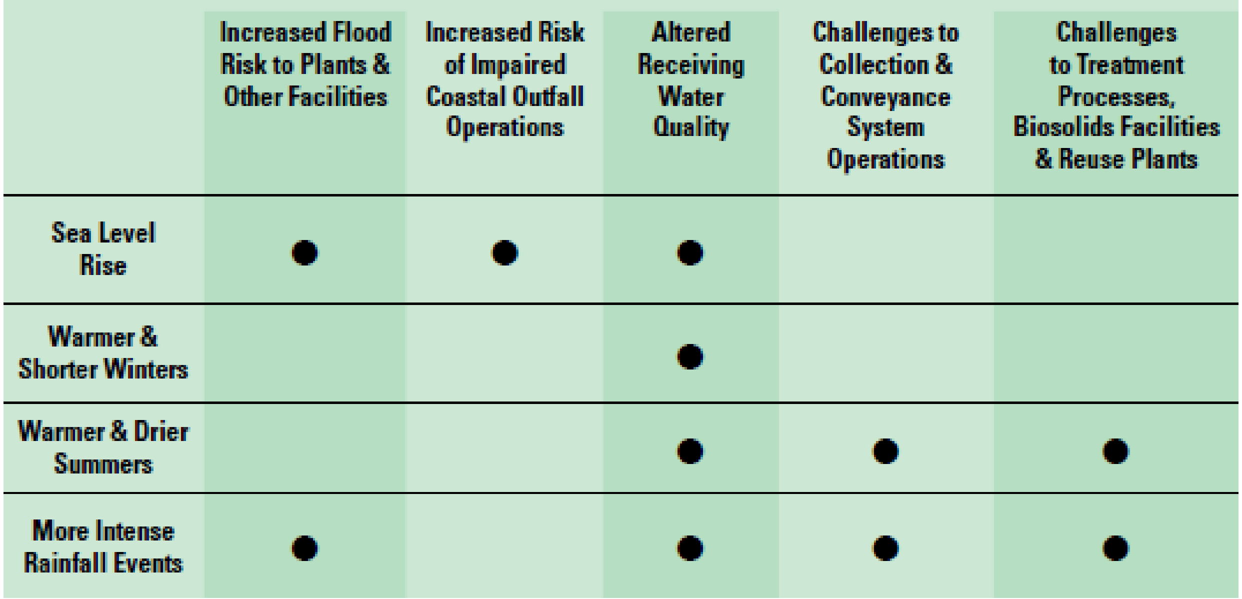
Many short-term adaptive measures involve improving the reliability, redundancy and resilience in facilities and operations. Especially when these options consist of low-or-no capital cost items and low-or-no carbon footprint items, they fall into a category called “low regrets’ or “no regrets” adaptations. Many such improvements in reliability are probably justified under current climate conditions. Climate change just provides one more reason not to hesitate with implementation. These adaptations can be readily justified as extending the useful life and value derived from existing assets, even in light of the uncertainties.

Changes in extreme events, for example, may not be gradual but could strike at any time. It is important to recognize that climate change includes long-term changes from greenhouse gases, but also climate variability. Another critical time dimension that should enter into the overall adaptation strategy is the remaining useful life of the current asset systems. If a new plant has just been erected by the sea, defensive facilities may be considered to protect the new asset from increased risk of storm damage. But if the seaside plant is older and in need of replacement, alternative plant sites or decentralized treatment might be alternative adaptation strategies to eliminate rather than mitigate vulnerability to storm surge.

In contrast, there are many climate change effects that will increase gradually as a function of temperature rise. For these effects, trend monitoring and incorporation into long-term asset planning may be adequate adaptations for now. It should also be acknowledged, however, that certain types of more sustainable future infrastructure – in particular green (or vegetative) infrastructure – may be best implemented gradually over a period of several decades, thus requiring an early start. And, yet another strategy that water management agencies can adopt in advance is to begin working more closely with one another and with local land use planners to consider collaborative adaptations at a watershed or regional scale to enhance their collective flexibility to meet change.

APPLYING THE RISK MANAGEMENT APPROACH

The cause-effect diagrams presented in the first half of this paper indicate a large number of potential impacts that may result from four sources of causation stemming from global warming. However, it is unwise to approach adaptation one dimension at a time because different climate change processes might affect a number of related variables. Table 1 offers a more practical summary, collapsing the four cause-effect diagrams (useful for risk identification) into a set of related “bundles” of climate change threats. The columns in Table 1 represent five major categories of potential threats to facilities and operations that require vulnerability and adaptation analysis (i.e., risk management). In the rest of this paper, each column is discussed individually to illustrate application of the risk management approach to the “threat bundles” represented in each column of Table 1 by the intersections with the rows.



	Increased Flood Risk to Plants & Other Facilities	Increased Risk of Impaired Coastal Outfall Operations	Altered Receiving Water Quality	Challenges to Collection & Conveyance System Operations	Challenges to Treatment Processes, Biosolids Facilities & Reuse Plants
Sea Level Rise	●	●	●		
Warmer & Shorter Winters			●		
Warmer & Drier Summers			●	●	●
More Intense Rainfall Events	●		●	●	●

Table 1. Implications of climate change for facilities and operations (WERF, 2010).

INCREASED FLOOD RISK TO PLANTS AND OTHER FACILITIES

Risk Identification

Many treatment plants and other wastewater and stormwater facilities have historically been located near major waterways for obvious reasons related to gravity flow. Such proximity gives rise to a concern for increased flooding of these facilities in the presence of a changing climate. As shown in Table 1, the increased risk of flood damage arises from two climate change influences – sea level rise and more intense rainfall events. These should be treated as separate adaptation issues except, of course, in the case of facilities located near the mouth of a large river on the coast where both risks may come into play. In addition, coastal erosion and loss of natural protective features such as barrier islands and wetlands is already progressing at alarming rates and is expected to continue as sea levels rise.

Risk Assessment/Characterization (Vulnerability Analysis)

What would represent a *threshold* level of flood damage to treatment plants, pumping stations or detention and drainage facilities that are vulnerable to these flood risks? What would be an unacceptable failure risk? Certainly damage at a level that causes a treatment plant to be knocked out of service for any period of time would qualify as a critical failure. Such a level of failure could cause broad environmental and public health damages. A lesser failure threshold might be conceived as a marginal degree of damage, sufficient to perhaps cause an episode of noncompliance, but more readily recoverable. Damage to collection and conveyance or drainage and detention facilities may or may not represent acceptable risk, but will surely increase maintenance needs.

What is the likelihood of seeing such *threshold* levels of flood damage within typical capital planning or other planning horizons?

Coastal erosion and increased flood risk from coastal storms are products of sea level rise. Sea level rise is expected to be gradual but the rate of change is uncertain (and a key reason is the potential contribution of melting of major glaciers in Greenland and Antarctica). Coastal storm intensity is also projected to increase gradually as a function of sea level rise, but there is a natural stochastic element in such phenomena that make it possible to see much stronger storms sooner than expected.

The same observations apply to increased flood risk produced by the increasing trend towards more intense rainfall events. Here too, there is a natural stochastic element that makes it possible to see larger floods sooner than expected. In fact, precipitation intensity has increased and there are indications that increased flooding has already been in evidence across the United States, based on trends in recorded streamflows.

Risk Management (Adaptation Analysis)

How can these increased risks of flood damage be met with adaptive responses? Regarding increased flood risk in general, it is a logical starting point for adaptation to undertake a review of emergency response plans to be better prepared for whatever the future holds. With respect to storm damage and coastal erosion from sea level rise, a review of protective measures to address the threat from erosive forces and storm surges during coastal storms may be warranted. This can include structural as well as non-structural approaches such as restoring wetlands in the vicinity of a plant or other facility.

Along rivers and flood plains, conventional flood control methods may become more critical in the short term as rainfall and runoff events continue to intensify. This includes both onsite defensive structures such as levees as well as upstream control facilities such as reservoirs. In addition, it is worthwhile to expand the long-term emphasis on non-structural approaches such as watershed scale land use planning and smart growth strategies, focused on reducing the amount of impervious area and encouraging a switch to green infrastructure where appropriate to dampen the compound impacts of climate change and growing populations on flood risks.

In the longer term plant replacement cycle, options might need to be expanded to incorporate elevation of key facilities, although this entails a carbon cost for pumping and there is a natural limit to this strategy – ultimately, wastewater treatment plants cannot be designed to look like drilling rigs. Relocation to upland sites or consideration of decentralized treatment options versus large downstream regional plants may come into play.

INCREASED RISK OF IMPAIRED COASTAL OUTFALL OPERATIONS

Risk Identification

Sea level rise will change the hydraulics under which many types of outfalls and stormwater conveyance facilities were designed to operate. The functioning of combined sewer systems – and of expensive modifications to combined sewer systems in coastal cities – is a particular concern in conjunction with the prospect of larger stormwater flows as a result of increased rainfall intensity.

Risk Assessment/Characterization (Vulnerability Analysis)

What would represent a *threshold* level of damage from improper outfall operation in coastal locations that are vulnerable to these risks? What would be unacceptable failure risks?

If outfall structures are unable to release discharges as fast as flows are entering at the other end of the pipes, flooding in streets and dwellings may result. Sewage back-ups and overflows pose additional risks in combined sewer systems. These are clearly failure scenarios to be avoided.

In addition to the risk of back-ups and overflows, there is the potential that an unlucky combination of wind, tidal and storm surge patterns could cause saline water to invade collection and conveyance systems. This risk might grow as sea levels rise. Not only is salt water corrosive to piping systems, but if it enters the wastewater treatment plant, it can cause great disruption of biological and chemical treatment processes.

When might you expect to see a *threshold* level of impairment of coastal outfall operations?

Operational impairment of coastal outfalls is expected to be a direct result of sea level rise. While the rise in sea levels is projected to be a gradual phenomenon, there is the possibility of more sudden changes due to faster melting of land ice in Greenland and Antarctica. Coastal storm intensity is also projected to increase gradually as a function of sea level rise, but there is a natural stochastic element in such phenomena that make it possible to see much stronger storms sooner than expected.

Risk Management (Adaptation Analysis)

How can you meet the increased risk of impaired coastal outfall operations with adaptive strategies?

Despite the gradual nature of the trend in sea level rise, the stochastic nature of storm events makes it prudent to initiate efforts to mitigate anticipated adverse impacts on coastal outfall performance. This is somewhat easier to engage since the costs of getting started are relatively modest. In the case of New York City and King County, Washington, both initiated their efforts with careful planning exercises to locate their outfalls using GIS tools and relate these locations to digital elevation data and storm surge data to evaluate the nature of the threat from the sea. Operational experiences with outfall performance under critical conditions was also examined in order to identify and prioritize the most vulnerable locations at which to begin applying adaptive measures, such as gates to prevent salt water inflow to the system. As always, where combined sewer systems are involved, the adaptive response might also include a redoubling of the commitment to green infrastructure and reduction of impervious surfaces as a means of diverting stormwater flows from the overloaded system.

Beyond the immediate priorities, the problem poses a number of planning challenges. Adaptation can include an array of defensive measures early in the century, leading perhaps to a re-configured coastal infrastructure during the next major replacement cycle. It goes without saying that such rearrangements of facilities will also change the carbon footprint of the resulting facilities. As many similarities as there are in the coastal setting, the examples to date also indicate that solutions are likely to be highly site specific.

ALTERED RECEIVING WATER QUALITY

Risk Identification

As illustrated in Table 1, everything resulting from climate change will contribute to baseline changes in receiving water quality which can have enormous significance for the wastewater and stormwater agencies, relating directly to regulatory compliance issues. At the most elemental level, the global increase in air temperatures will produce increased water temperatures and lower dissolved oxygen. Estuarine waters will become warmer as well as more saline due to sea level rise and also more acidic due to CO_2 absorption. Generally warmer air during both winter and summer seasons may produce local or regional variations in air circulation patterns that will, in turn, produce changes in pollutant loadings contained in rainfall (e.g., nutrients, acidity, etc.).

Warmer and shorter winters will result in smaller snowpacks, earlier spring melt and less groundwater recharge, producing lower base flows in many rivers during the late summer and fall. Warmer and drier summers will further increase the risk of extreme heat waves and drought conditions in many regions of the country, altering water temperatures and concentrations of water quality parameters during extreme low flow conditions.

Warmer and drier summers will also contribute to increased eutrophication of surface water bodies. This effect can be magnified by climate induced changes in watershed conditions. The changes in temperature and rainfall are likely to produce changes in natural vegetative cover that could have effects on water yield and quality. The risk of wildfire is known to increase under warmer and drier conditions and wildfires can be a major source of nutrient and sediment loads that can be sustained for years following an event. Finally, agricultural and irrigation practices are likely to adapt also, producing a different pattern of non-point pollution loadings.

More intense rainfall events are troubling because of the compliance challenges associated with wet weather flows through treatment plants and because of consent decree requirements governing the control of overflows from combined sewer systems. However, these direct compliance challenges of more intense rainfall – discussed below – also affect wastewater and stormwater agencies indirectly to the extent that the same problems occurring upstream of their location can alter the receiving water quality at their downstream location.

Risk Assessment/Characterization (Vulnerability Analysis)

What would represent a *threshold* level of climate-induced deterioration in receiving water quality? What would impose an unacceptable failure risk on existing wastewater and stormwater management facilities sufficient to impair their ability to sustain regulatory compliance or meet water quality goals?

The Clean Water Act strives to attain and sustain water quality goals in the receiving waters of a wastewater or stormwater agency. As described above, there are so many climate induced threats to baseline water quality, it is conceivable that adverse trends might eventually cause the regulatory process to respond in some manner. It may be temperature, or dissolved oxygen, or bacteria, or nutrients – or compounded effects due to low base flows and high wet weather flows. It may be that state water quality standards will eventually have to be revisited to make a realistic appraisal of the attainability of designated uses in a changing climate. Alternatively, the regulatory process could require upgraded performance from existing wastewater and stormwater facilities via tighter NPDES or MS4 permit requirements or TMDLs in order to hold the line on ambient water quality. As discussed further, below, that is not to say that more effort would not also be required of non-point sources, but the critical threshold for existing wastewater and stormwater facilities would be the point at which regulators would be forced to require expensive modifications.

When might you expect to see a *threshold* level of deterioration in receiving water quality such that regulators might be compelled to require expensive modifications of existing wastewater and stormwater facilities in order to offset climate-induced adverse trends in ambient water quality?

The spectrum of potential adverse effects of climate change on receiving water quality is so broad as to be truly daunting in its complexity. It will be very difficult to detect and attribute changes in baseline water quality to – in this instance – mostly gradual climatic, hydrologic and ecologic changes as well as climate induced changes in anthropogenic activities that affect water quality (land use, agriculture and forestry). It will indeed be difficult to say when this critical threshold level of impact has been reached – due to climate change.

Risk Management (Adaptation Analysis)

How can you adapt to meet the threat of a *threshold* level of climate-induced deterioration in receiving water quality that would result in new regulatory requirements for costly upgrades to existing wastewater and stormwater facilities?

Because this is more likely to be a gradual change process for most phenomena, there is time to improve knowledge before adaptive responses are compelled by circumstances. The need for research extends beyond the US EPA, WERF and other nationwide basic research sources, however. Every wastewater and stormwater agency should consider the question of potential climate-induced impacts on receiving water quality and identify their own research needs to assist them in gaining a preview of the future through watershed monitoring and modeling that will better enable them to anticipate a critical threshold level of change in receiving water quality. Watershed scale cost sharing among water supply, wastewater and stormwater agencies might help break the cost of this particular adaptive strategy.

In many instances, the attainability of use designations established for water bodies under state water quality standards was never fully scrutinized under assumptions of stationary climate. With the broad array of threats to receiving water that could conceivably arise in a changing climate, these foundation issues in the establishment of water quality standards may be impossible to ignore. Active involvement of State and EPA regulators and watershed stakeholders in the design and implementation of enhanced monitoring and related research will be key to all parties concerned in evaluating the possibilities for changes in the regulatory program. It is conceivable that different regulatory approaches will be more appropriate to a changing future, involving more reliance on such techniques as watershed based permitting, trading and other innovations. It is also conceivable that in some areas of gradual change, the main responsibility of the current generation of water professionals will be development of trend data to support later adaptations in facilities, operations and regulatory institutions.

A second step in adapting to meet this threat is to carefully re-examine the remaining useful life and planned rehabilitation / replacement cycle for all facilities that can conceivably be affected by this threat. Given the anticipated gradual nature of the threat, it is possible that the changes required can be efficiently integrated into normal asset management and capital planning processes and that the extra expense of unplanned modifications can be avoided. The wet weather issues stemming from increased rainfall intensity may be the exception in places where it appears this change is already underway.

Finally, in adapting to meet this challenge wastewater and stormwater agencies need to recognize that this threat – as defined above – is based on a business-as-usual extrapolation. But the future does not have to simply replicate a past in which every wastewater and stormwater agency works alone and fends for itself. It is possible to conceive of an alternative future based on watershed scale collaboration, involving not only regulated point sources, but non-point sources and other influences totally outside the regulatory regime such as land use planning authorities and other interested stakeholders. By expanding the system boundary in this manner, the range of possible adaptive strategies may be expanded to the benefit of all concerned.

CHALLENGES TO COLLECTION AND CONVEYANCE SYSTEM OPERATIONS

Risk Identification

Table 1 indicates climate-induced challenges to collections and conveyance system operations will likely result from both the dry spells associated with warmer and drier summers as well as from more intense precipitation events when it does rain. These are two different impacts involving totally different mechanisms, but resulting in increased stresses on the same pipe infrastructure systems.

Risk Assessment/Characterization (Vulnerability Analysis)

What would represent a *threshold* level of climate-induced impact on collections and conveyance system operations that would produce an unacceptable level of failure risk?

As temperatures continue to rise over the century, warmer and drier summers are predicted in almost all parts of the country. Even many areas projected to receive more rainfall overall are projected to be drier in summer. Many places will also be subject to increase drought risk and risk of more intense heat waves and dry spells. The net effect could be damaging to pipe infrastructure. Water conservation efforts could greatly reduce flows in sewers designed to carry higher volumes. The additional air space and longer dwell time in the piping system could create greater opportunities for septic odor problems and for pipe corrosion due to formation of hydrogen sulfide and sulfuric acid. In addition, more frequent and extreme dry spells could stimulate the growth of deeper root systems causing increased penetration and blockage of sewers.

The acceleration of the hydrologic cycle caused by warmer temperatures will produce more intense rainfall events. This trend is already apparent in precipitation records. If such extreme rainfall events follow extreme dry spells, there may be accumulations of material in some pipes that could cause local back ups and/or surge loadings to treatment facilities. Agreements with industrial sources may be affected by such anomalies that were not anticipated when arrangements were established to accept industrial flows. With or without pretreatment, industrial flows were probably accepted on the basis of the flow regimes in the conveyance system that exist under current climate. Altered flow regimes may upset those arrangements.

Although most wastewater and stormwater flows by gravity, pump stations are a critical part of the conveyance infrastructure. There is clear threat to the performance of this infrastructure if flows are either much smaller or much greater than estimated when the pumping facilities were designed under assumptions of stationary climate. Overflows, backups and equipment damage could result.

In addition, there is a concern that an increasing trend towards more intense precipitation was not recognized and taken into account in the design of many remedial programs developed to address combined sewer overflows and sanitary sewer overflows. If the planned corrective measures are under designed, then the significant expenditures entailed could result in less improvement in water quality than anticipated.

When might these *threshold* levels of climate-induced impact be expected to appear in the operations of collections and conveyance infrastructure?

Although both of these effects are already in evidence, the increased incidence of both dry spells and more intense rainfall events are generally regarded as gradual changes. However, both of these phenomena are subject to stochastic influences that could produce events that are more extreme than expected. Despite these factors, the threshold levels of impact required to produce serious damage to pipe infrastructure or sustained violations will probably take time to become manifest. For the most part, these are impacts for which there is time to deploy an adaptive response.

Risk Management (Adaptation Analysis)

How can you adapt to meet *threshold* levels of climate-induced challenges to collections and conveyance systems from abnormally low or abnormally high flows?

The increased threat to the physical integrity of pipe infrastructure from both corrosive action and tree roots suggests that augmentation of the inspection and maintenance elements of the asset management program would be an excellent “no regrets” adaptation. In consideration of the potential problems caused by deposition of materials during extreme low flows, enhanced maintenance and cleaning programs may be justified from another important perspective.

The increased threat of sewage overflows during extreme rainfall events will first require careful study to evaluate how much buffer is believed to exist to absorb high flow events without triggering violations. The question then becomes one of how much of that capacity could be lost to climate-induced rainfall intensity and how it can best be recovered. It is conceivable that, under the right conditions, the long term answer may lie in green infrastructure strategies designed to reduce runoff and prevent it from entering combined sewers or leaky sewers. As more and more green infrastructure is added to such a program year after year, it may be capable of keeping up with the gradually increasing rainfall intensity phenomenon over the course of time.

CHALLENGES TO WASTEWATER TREATMENT, BIOSOLIDS AND REUSE OPERATIONS

Risk Identification

As shown in Table 1, treatment, biosolids and reuse operations will also be impacted by the odd combination of warmer and drier summers – carrying the risk of more extreme heat waves, dry spells and drought risk – together with increased wet weather operating challenges caused by more intense rainfall events. Both types of extremes are capable of presenting a broad range of process operating challenges with complex effects. Climate change delivers both.

Risk Assessment/Characterization (Vulnerability Analysis)

What would represent critical *threshold* levels of key influent and operating parameters during extreme dry weather conditions and extreme wet weather conditions – threatening process failure in the absence of adaptive responses?

Wastewater treatment plants, biosolids management facilities and reuse treatment plants are all designed on the basis of an assumed range of flow rates, temperatures, and biological and chemical influent characteristics. Some types of processes are more tolerant of variations in these parameters than others. Going forward under climate change, it must be taken as a given that there will be an increasingly wide operating challenge presented by variability in the influent stream. In addition, the natural relationship between operating temperatures and oxygen transfer efficiency could affect treatment and biosolids processes, disturbing process control and potentially producing anaerobic conditions and odor control issues.

During extended dry spells and drought periods a much stronger and smaller waste stream is to be expected as a result of likely implementation of conservation measures. But when it rains, the intensity of rainfall and runoff might produce initial surge loadings from material deposited in conveyance facilities followed by excessive volumes of dilute waste at extraordinary flow rates. It may be necessary to swing rapidly from one operating mode to the other, increasing the risk of operating errors. As conditions progress, it may become clear that either a treatment plant or biosolids processing facility or land disposal site or reuse facility designed under historic climate assumptions is not suited to these extreme operating modes without adaptation. Land disposal of biosolids and odor control facilities may be particularly challenged by rapid shifts between wet and dry conditions that will also affect soils, vegetation and insect pests.

All of the above issues have implications for industrial sources as well. Direct dischargers will face all the same challenges in their treatment processes. Industrial sources contributing wastes (with or without pretreatment) to municipal wastewater systems may find that the additional operating challenges at the municipal plant have repercussions in terms of future arrangements regarding the timing and strength of their allowed waste flows into the system.

When might these erratic changes in operating conditions be expected to present a critical *threshold* level of challenge to treatment, biosolids and reuse facilities?

The increased incidence of both dry spells and more intense rainfall events is already in evidence and will likely increase as temperatures increase. However, both of these phenomena are subject to stochastic influences that could produce events that are more extreme sooner than expected. Despite these factors, the threshold levels of impact required to produce serious process operations difficulties will probably take time to become manifest. For the most part, these are impacts for which there is time to deploy an adaptive response.

Risk Management (Adaptation Analysis)

How can you adapt to meet *threshold* levels of climate-induced challenges to treatment plants, biosolids facilities or reuse plants from abnormally hot and dry or abnormally wet weather?

A vulnerability analysis of treatment, biosolids and reuse facilities is a good way to determine adaptation needs. Examining the existing design and operations, it is prudent to look at all the key parameters to see if there are weaknesses in the process concept that would be stressed by sudden shifts between extreme operating conditions and then identifying operating practices and perhaps plant modifications to meet these challenges. Because these impacts are expected to arise gradually over time, there may be an opportunity to fold capital modifications into routine rehabilitation/replacement cycles rather than identifying them as additional capital demands.

Significantly, there are at least three major sets of constraints that will have a bearing on the extent of flexibility available in modifying the operations of treatment facilities. First it is apparent from previous discussion of the challenges presented from changes in receiving water quality that the extreme variation between wet and dry inflows to a plant discussed here are only one part of the overall performance challenge to be faced; the receiving water quality that drives treatment standards will be simultaneously impacted by the same extreme phenomena. A second set of constraints is imposed by the fact that process changes in wastewater treatment may change the character of the outputs that are provided to downstream biosolids and reuse facilities. Too much change in the nature of the treated products may create the subsequent need for changes in these downstream processes. Finally, wastewater treatment and biosolids processes have been the center of much attention regarding the minimization of green house gas (GHG) emissions. Process changes to meet water quality objectives as adaptations to climate change must be factored into these quite complex process optimizations that have single-mindedly targeted GHG reductions because the two goals may conflict in a number of places.

CONCLUSIONS

Global warming is expected to result in sea level rise, warmer and shorter winters, warmer and drier summers, and more intense rainfall events. These changes may produce a cascade of secondary effects in hydrologic and environmental processes. The uncertainty in climate forecasts is dwarfed by the complexities of tracing climate effects through hydrologic and environmental processes to predict how they may change the operating conditions facing wastewater and stormwater agencies. Climate change presents a much greater degree of uncertainty than is typically encountered in facilities and operations planning. How do you prepare for changes of unknown magnitude on an unknown timeline? There is a great temptation to wait and see if climate science can be improved to provide a better basis for action. But significant improvements in climate forecasts are not likely in the near–term and much of the uncertainty arises in predicting the secondary effects as climate changes are manifest through Earth systems. Hence, it would be a mistake to just ignore climate change and resume a business as usual approach to planning. The familiar risk management paradigm – consisting of risk identification, risk assessment/characterization, and risk management – can be effectively applied to these new threats, enabling wastewater and stormwater agencies to identify their most sustainable path for the future despite the inherent uncertainties.

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