The Infrastructure Planning Support System (IPSS^{TM})

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Introduction

The Infrastructure Planning Support System (IPSS^{TM}) was created by researchers at the University of Colorado Boulder in 2011. A quantitative, engineering-based analysis tool, IPSS is designed to help users understand the complex impacts of climate change on transportation, building, and energy infrastructure. IPSS broadens the criterion and methods of traditional infrastructure resiliency analysis by including the analysis of climate change impacts and adaptation opportunities. Specifically, IPSS isolates the incremental costs of climate change in terms of maintenance to infrastructure as well as to interruptions caused by impacts to workforce and mechanical systems. In addition, rather than limiting the scope of climate change analysis to a few scenarios or a selected set of stressors, IPSS has the flexibility to utilize multiple climate scenarios or custom suites of scenarios. IPSS also diverges from traditional efforts by taking a more holistic, life-cycle approach to infrastructure analysis and taking into account all phases of the planning cycle (short, medium, and long term). This enables IPSS to look at multiple adaptation scenarios for each type of infrastructure in addition to just the risk posed by climate change. By integrating expertise from climate science, engineering, water resources, architecture, economics and other fields, IPSS produces actionable guidance to assist decision makers in planning for climate change.

The IPSS system has been utilized in a number of studies in countries and regions across the globe, including: the Netherlands, Africa, South Africa, Ghana, Vietnam, Mongolia, China, and the United States. These studies have been commissioned by the World Bank, Asian Development Bank, Canadian Government, United States Environmental Protection Agency, United Nations University, and others (Melvin et al 2016; Cervigni et al 2016; Chinowsky and Arndt, 2012; Chinowsky et al., 2011, Chinowsky et al., 2012, Chinowsky et al., 2013a, Chinowsky et al., 2013b; Industrial Economics, 2010; Hughes and Chinowsky, 2012; Kwiatkowski et al., 2013; Stratus Consulting, 2010; Westphal et al., 2013; World Bank, 2010).

The broad use and applicability of IPSS is attributed to the system being designed for use by a range of transport and policy practitioners. Analyses can be conducted for a variety of spatial resolutions or geographic areas (e.g., climate grid level or climate zone, county, state, country, or region). In addition, IPSS can incorporate projections from any number of global climate models. The default analysis includes historic climate data as well as projections from a suite of models from the Intergovernmental Panel on Climate Change's (IPCC's) Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012). These models project daily climate conditions through 2100 for stressor variables relevant for infrastructure analysis, including precipitation and temperature. The standard analysis evaluates the impacts of these climate stressors on nine types of roads, including a primary, secondary, and tertiary classification for paved, gravel, and earth roads.

IPSS can be run at either the portfolio level or an individual asset management level. In the former, the model can run inventories of thousands of elements (such as buildings, miles of roadway, bridges, miles of rail) and analyze the elements from a grid perspective where all similar element types in a grid are analyzed together for overall vulnerability and initial resiliency studies. In the latter mode, the system can be used on an asset level where each asset is defined in terms of cost and life-cycle properties. Each asset can be analyzed using default or custom adaptation and cost profiles, enabling the user to perform multiple scenario planning exercises. This combination provides the flexibility to utilize IPSS either at a planning or operational mode depending on user requirements.

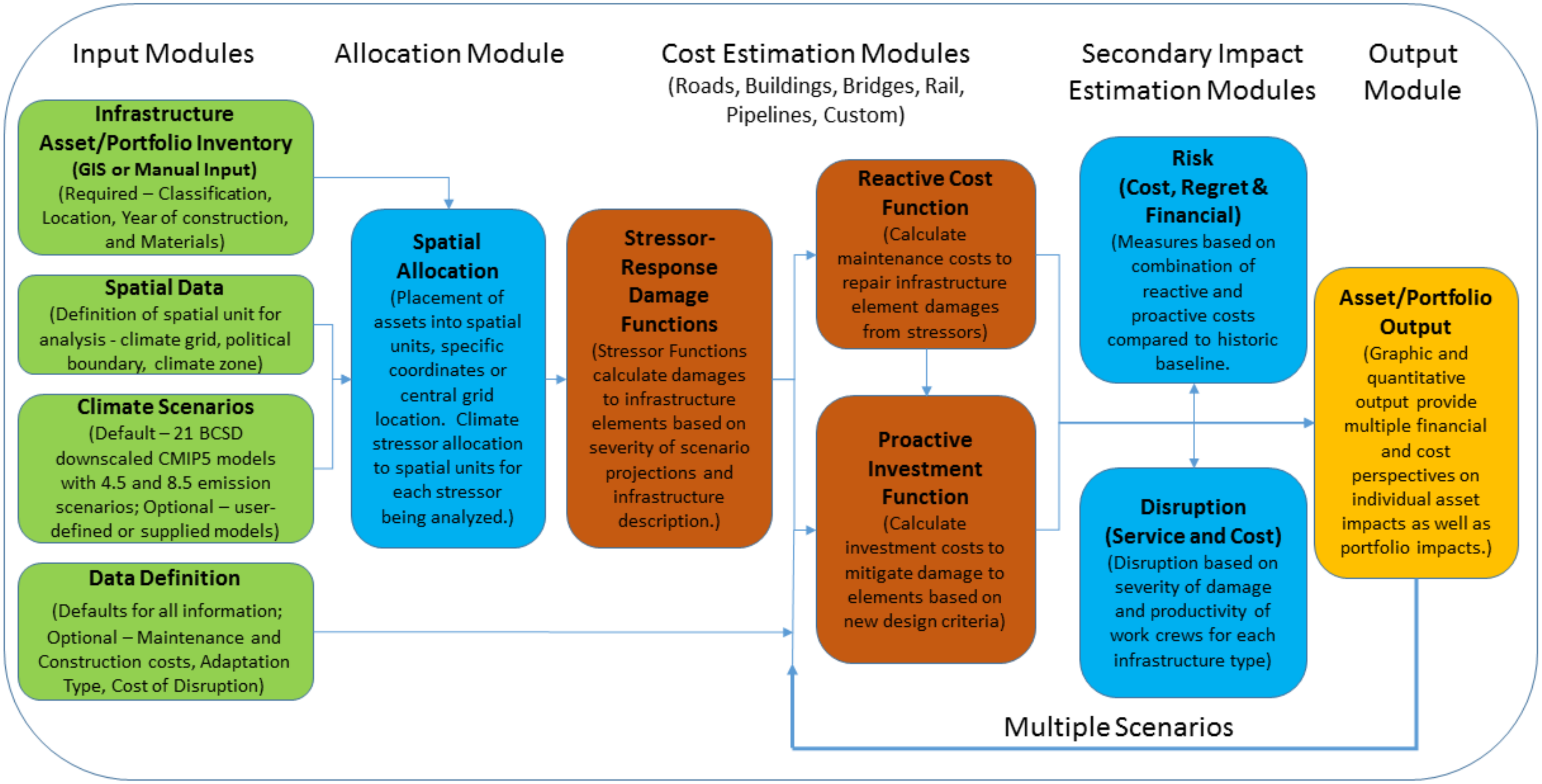
A number of modifications can be made to customize the base IPSS analysis. If specific cost and stressor-response functions are available for infrastructure in a specific area, these can be defined by the user. The default is defined through a robust set of research reflecting international standards for each infrastructure type and climate-stressor impact (Arndt et al., 2012; Chinowsky et al., 2011; 'IPSS'; Chinowsky and Arndt, 2012).

The input interface allows a user to select analysis options such as the discount rate, types of infrastructure to adapt, growth rates for infrastructure, which climate models to analyze, and the types of output information that are desired. Users can provide the models with custom cost information as well as information to determine cost of disruption for each asset including traffic rates and cost of delays for transport assets, daily use of building assets, and number of bridge crossings for bridge assets. For each type of asset, productivity rates can be entered for construction crews to determine length of disruption. Additionally, custom adaptation measures can be simulated to provide specific scenario planning for individual assets or portfolios of assets.

An Overview of the IPSS System

The IPSS system comprises five modules, each designed to support a specific element of the analysis process. The modules are intended to be modifiable to meet the changing needs of users. Figure 1 presents a schematic representation of the IPSS system. The following sections describe each module, including the functionalities and underlying conceptual frameworks.

Figure 1: Overview of the IPSS system



Input Modules

The input modules provide the capability to input specific inventory, climate thresholds, damage levels, and spatial data into the system. Of these, only the inventory is required as all other data can be derived from default information within the system. However, the greater the granularity of information provided to IPSS, the more specific the output will be to the individual case being analyzed.

As detailed in the sections below, IPSS contains multiple types of datasets as default values for the overall system. However, each of these datasets can be overridden and replaced either in total or with specific pieces as per user requirements. In addition to the climate datasets which are described below, IPSS incorporates a broad set of data on costs, productivity rates, adaptation strategies material responses, and historic practices from recognized data sources. Where possible, IPSS utilizes commercial and public data sources such as the World Bank (HDM Global 2021; ROCKS 2021) for global costs and productivity rates and RS Means (Gordian 2021) for domestic costs and productivity rates. These sources are augmented and refined with local cost and productivity data where possible.

For example, local data are often provided by government ministries or aid offices for international projects, or by state DOTs, local public works departments, and specific oversight agencies for projects in the U.S. For surface transportation, the majority of data is obtained from agencies such as the US Federal Highway Administration, and the US Army Corps of Engineers, as well as similar agencies within international locations. Building guidelines are derived from International Building Codes as well as local regulations where appropriate. Similarly, bridge and pipeline information is obtained from national and local agencies.

Finally, the response curves, as documented below, are also derived from publicly-available materials and performance studies. As detailed in each section, sources include peer-reviewed journal studies, agency studies, manufacturer guidelines, and regional studies where local conditions such as erosion and fire concerns provide additional information.

Inventory Input

IPSS is designed to analyze infrastructure inventories at either the portfolio level or the asset level. Examples of the former include paved secondary roads, hospitals, or class 1 rail lines. To analyze impacts on an inventory of infrastructure, the user inputs information on the inventory including the type of infrastructure (e.g., paved secondary roads), the total quantities of the infrastructure in the inventory (e.g., miles of roadway), and the location of the roads (e.g., the state of Massachusetts). The user may also specify information on the condition of the infrastructure. The inventory may be provided in a Geographic Information System (GIS) file, as described below, which allows the system to allocate the assets based on the coordinates provided in the GIS file. IPSS then commences the analysis of the portfolio assets allocated to their respective locations, but reporting remains at the aggregate portfolio level.

For analyses of individual assets, the user inputs information on the type of asset, location, year of construction, and condition. If multiple assets are entered, each asset is analyzed separately to enable results to be generated at both the individual asset level as well as aggregated levels as defined by the user.

Spatial Data

The second element in the Input Module is a definition of the spatial resolution at which the analysis will be conducted and reported. IPSS is flexible in that it can perform an analysis at any spatial resolution or set of natural or political boundaries. The default mode of IPSS is to work at a spatial grid level. In this mode, all infrastructure inventory and all climate data is placed on a common grid enabling analysis to be coordinated between the two primary data sets. IPSS has been deployed at multiple grid cell resolutions ranging from a custom climate data resolution of $1/16^{th}$ of a degree to a much coarser grid definitions.

Although all infrastructure inventories or assets being analyzed are placed into grids for analysis, grid cells can be aggregated for reporting if desired. For example, grid translations have been deployed for IPSS projects to political definitions including counties, states/provinces, and national boundaries as well as climate-based spatial definitions such as Koppen-Geiger climate zones and ASHRAE climate zones. The underlying grid definition provides IPSS with the flexibility to output results at any of these types of spatial resolutions. If no alternate definition is provided, IPSS uses a quarter degree by quarter degree grid for the underlying analysis and the output is provided at either the individual asset level or at an appropriate political level based on the underlying analysis.

Climate Scenarios

IPSS includes a default set of climate projections from IPCC's Fifth Assessment Report (AR5) (Taylor et al. 2012). Two "Representative Concentration Pathways" (RCPs) are incorporated to capture a range of uncertainties and plausible emission futures. The RCPs are identified by their approximate total radiative forcing in the year 2100, relative to year 1750: 8.5 W/m^2 (RCP8.5) and 4.5 W/m^2 (RCP4.5). RCP8.5 implies a future with continued high emissions growth with limited efforts to reduce GHGs, whereas RCP4.5 represents a global GHG mitigation scenario. Neither of these scenarios represents any particular national or global policy.

To ensure that the climate projections are applicable to infrastructure scale decision-making, IPSS utilizes downscaled projections produced by the NASA Earth Exchange Downscaled Climate Projections for global efforts (NASA 2021) and the Localized Constructed Analogs (LOCA) for efforts within the United States (LOCA 2021). Each of these downscaled sets incorporate Bias-Correction Spatial Disaggregation (BCSD) techniques to provide detailed projections at a local scale.

In addition to these default climate projections, users can provide additional climate data for inclusion in the analysis process. The data sets can be in a time series or era format. The data can be at any spatial grid level, however a conversion table must be created to coordinate the climate grid with the inventory analysis grid.

Data Definition

The last component of the Input module comprises the input for the Data Definition. Each element of the infrastructure inventory analyzed or each asset analyzed requires information on cost, condition, and disruption. IPSS includes default values for each of these parameters that can be overridden with location-specific data if available.

Information on cost includes original construction costs, adaptation costs, and maintenance and repair costs. The default cost values have been obtained through a number of sources depending on geographic location, including the World Bank, local data sources, and commercial cost databases. The condition parameters include the year of construction or planned construction, a qualitative evaluation of the infrastructure element if it is currently in place, and the design lifespan of the element.

Finally, disruption parameters including traffic levels and cost of transport that is related to that geographic location are utilized to develop cost impacts from delays caused by increased maintenance or construction activities. Although defaults exist for these parameters, the system is best utilized by providing values that reflect local conditions.

Allocation Module

After the user enters all of the required information in the input modules, the first step of the analysis is to align the infrastructure data with the climate data on the defined spatial allocation units. As stated previously, the base unit in the IPSS system is a grid system that serves as a common unit for both climate and infrastructure data. The grid unit selected for an analysis is typically that of the climate scenarios to eliminate the need for further downscaling or aggregating of the climate projections. This process is outside the scope of the IPSS system and thus requires external analysis to develop new spatial allocations for climate scenarios. The default grid unit utilized in the IPSS system is currently quarter degree by quarter degree.

Given the spatial grid for a given analysis effort, each infrastructure element is assigned to a corresponding grid cell prior to IPSS impact analysis. When the exact location of an infrastructure element is provided through spatial coordinates, the infrastructure element is assigned to the corresponding spatial grid cell. For roads, railroads, and pipelines, these elements often span multiple grid cells and therefore each piece of linear infrastructure is divided into sections according to the grid cells that it crosses. As discussed below, the analysis of impacts is conducted at a grid level so the exact location within a grid cell does not impact the final result. Therefore, having the exact location of an infrastructure element is not critical. Rather, having locations within the granularity of the spatial grid are required to generate representative output.

When the location of infrastructure elements is not specifically known, then a spatial allocation methodology is employed by IPSS to allocate infrastructure to individual grid cells. This conversion is typically required in a portfolio analysis when the total amount of infrastructure within a political unit is known, but the exact allocation is not available. In these cases, the grid cells that represent the political unit defined by the portfolio such as a state or county are identified as potential locations for infrastructure allocation. The infrastructure elements are then evenly distributed across those cells as an initial allocation. As a refinement to the spatial location, the infrastructure elements can be adjusted based on population patterns. This approach may influence damages and adaptation cost estimates due to specific infrastructure elements being placed in grid cells that are different from actual locations. However, this variation can be reduced by the use of a more granular political boundary. Thus, a city-level portfolio will have fewer spatial misallocations than a state or region.

The conclusion of the spatial allocation process results in coordinated grid system of climate data and infrastructure elements. The allocated grid will also serve as the base units for aggregation in the output modules where results from IPSS analysis runs can be reported in any aggregation of the spatial units defined in the allocation process.

Cost Estimation Modules

The core of the IPSS system is the estimation of quantitative impacts resulting from climate change. Conceptually, the cost estimation process follows the same three-step process of damage estimation, cost impact, and adaptation analysis for every type of infrastructure. In the first step, the level of potential damage is determined based on the difference between future conditions defined by the climate scenarios and the historic environment, and how that difference affects the as-designed condition of the infrastructure. This analysis involves looking forward across the lifespan of the infrastructure being analyzed and assessing how climate change will affect it based on “perfect foresight” of how climate change impacts will manifest. Once potential damage is determined, IPSS estimates the costs associated with two different strategies: proactive adaptation and reactive adaptation. Both strategies are analyzed with the goal of retaining the original design life and service level of the infrastructure despite climate change-related impacts.

In the proactive adaptation strategy, infrastructure is changed during the original construction phase or the scheduled rehabilitation point to increase its resilience to projected climate change impacts. In the reactive adaptation strategy, no changes are made to infrastructure to increase its resilience and, instead, any climate change impacts are addressed through increased maintenance and repair of damages. This approach is often thought of as a “business-as-usual” approach to climate change. In both strategies, the cost of climate change is based on the actions needed to maintain the design lifespan of the infrastructure.

IPSS incorporates a refinement of the adaptation planning process which incorporates a time consideration. Specifically, IPSS determines when an impact will occur that requires adaptation and then implements the proactive changes in the time period in which the adaptation is appropriate based on impact projection and rehabilitation or construction schedule. In this manner, IPSS does not implement proactive adaptations prior to the time in which the investment is required and justified.

Stressor-Response Damage Functions

IPSS predicts the impact of the climate change stressor on the infrastructure inventory by using engineering based stressor-response equations. These equations reflect the response of the infrastructure materials to the climate impact stressors, and have been developed using a combination of previous research on materials science, case studies and historical data. Impacts are determined for each type of infrastructure (e.g., roads, bridges, rail, pipelines, and buildings) and each climate stressor directly (precipitation and temperature) and indirectly (flooding, water flow, freeze-thaw) and for each spatial grid unit as defined in the Spatial Allocation step described above. Specific response equations, thresholds and methodologies are detailed in previous work (Melvin et al 2017; Cervigni et al 2016; Schweikert et al. 2014; P. Chinowsky and Arndt 2012; P. S. Chinowsky, Price, and Neumann 2013; P. Chinowsky et al. 2013; P. Chinowsky et al. 2011). As detailed in these studies, the underlying concept behind the stressor-response methodology is that as long as a relationship can be defined between a stressor and an infrastructure type, then a damage function can be created for the IPSS engine. In this manner, relationships have been defined for each stressor and each type of infrastructure where applicable, and continue to be added as new infrastructure types or geographic-specific or user-defined relationships are required.

To provide an overview of the stressor-response damage estimation process, an example using paved roads provides a common illustration for the overall process. A similar process is used for all types of infrastructure addressed within the IPSS system.

For road infrastructure, the stressor-response functions are divided into functions for paved (asphalt and concrete are addressed separately), gravel, and unpaved roads. Within each of these categories, refinements are made for primary, secondary, and tertiary roads. To illustrate the damage function process, the effect of increased temperature on asphalt pavement in the United States is provided. Where temperatures are expected to increase, the lifespan of the road will be decreased due to increased degradation of the surface when road temperatures exceed design parameters. For the United States, the guidance used is from the *Superpave* increments of pavement temperature (Transportation Research Board 2005). When pavement temperature is predicted to increase above a design threshold over the design level calculated by historic temperatures, increased degradation is calculated based on published material studies (Miradi 2004). For the temperature example, the degradation is the projected increase in raveling and cracking that will occur due to pavement weakening.

IPSS estimates this condition based on the historic and projected 7-day maximum ambient temperatures calculated for each grid for each climate change scenario. These 7-day maximum temperatures are then used for the relationship between pavement temperature and ambient temperature (Lavin 2003). Based on the historic and projected temperatures, IPSS can determine if the pavement mix thresholds have been exceeded and to what extent.

$$Tp = 0.9545\,(Ta - 0.00618\,L2 + 0.2289\,L + 42.2) - 17.78 \qquad (1)$$

Where:

Tp is the pavement temperature (°C)

Ta is the ambient temperature (°C)

L is the latitude (arc degrees)

The threshold approach allows IPSS to determine when a projected change in climate parameters will be significant enough to cause climate-based damage to infrastructure elements. Each stressor and infrastructure type have different thresholds based on the manner in which stressors affect given materials or design standards. For example, bridge piers have flow rate thresholds based on scour potential while building drainage systems have maximum precipitation thresholds related to typical drainage design standards. Appendix A has a list of the stressors and the infrastructure types related to those stressors in terms of default damage estimation functions.

Proactive Cost Estimates

The proactive adaptation strategy included within IPSS involves changing the design and construction approach when an asset is scheduled to be built or rehabilitated with the goal of making it more resilient to projected climate change impacts. Proactive adaptation costs include the additional costs required to adapt design and construction to mitigate against projected changes in climate expected to occur over the asset's lifespan. These adaptation costs are only incurred if climate change impacts are projected to affect the infrastructure during its design lifespan.

The derivation of the stressor-response values for new construction costs encompasses two general approaches. Each approach retains the focus of building a new infrastructure component to a standard that enables it to withstand projected climate changes over its design lifespan. The first approach estimates stressor-response values based on the cost associated with enhancing materials selected or design requirements, while the second emphasizes adaptation to an alternate infrastructure type. The enhancement approach generates stressor-response values for infrastructure elements such as bridges and paved roads. In this approach, infrastructure is designed to a level that protects against the future changes in climate conditions and the accompanying changes in material or design requirements. For example, an increase in predicted flood levels will require an increase in culvert size to mitigate damage to an associated roadway. The cost of increasing the size of the culvert as well as the associated increases in construction costs is considered the proactive adaptation cost for that roadway in response to the flooding stressor. This methodology similarly determines if any new or rehabilitated structures, such as paved roads, will be subject to material changes when it is anticipated that a significant climate change stressor will occur during the lifespan.

Similarly, the second option for proactive adaptation for new construction is to alter the type of infrastructure being constructed to one that has the capacity to handle the anticipated climate change. For example, if climate change is anticipated in an area with dirt roads, then a consideration has to be made for either increasing maintenance costs or altering these roads to gravel roads. For the gravel road option, the cost of adaptation is based on the need to strengthen the road with a crushed gravel mix. The benefit with this approach is that basic maintenance as well as climate induced maintenance is eliminated on the dirt road (because it has been adapted). Maintenance costs may return if climate impacts increase to exceed the level of the gravel road at which time adaptation may be considered to upgrade the surface to the next level.

In general, proactive adaptation is defined for the IPSS-based analysis as an infrastructure element where design changes have been made to withstand projected changes in climate stressors throughout its design lifespan. Once an adaptation investment has been implemented, the infrastructure element is considered resilient to the projected changes in climate. The only exception to this is if events occur that are greater than the adaptation threshold, but less than a second threshold of adaptation, then residual costs may exist for additional maintenance not covered by the adaptation strategy. The benefit of the proactive adaptation approach can be determined by calculating the difference in the cost between the maintenance and repair costs incurred under the reactive adaptation approach (discussed below) and the investment cost for the proactive measures. There are some cases where a proactive adaptation approach leads to significant savings, and others where it is more expensive than reactive adaptation.

Importantly, IPSS only adapts infrastructure at the time it is scheduled for rehabilitation or at new construction. IPSS does not rebuild infrastructure in the middle of its design lifespan. Additionally, in cases where the cost of proactive adaptation for a portfolio of assets is too high for a single year, IPSS has the ability to incrementally apply adaptations to a percentage of assets each year over a period of several years.

Reactive Cost Estimates

In the reactive adaptation strategy, infrastructure is not modified during the design or construction phase to increase its resilience; rather, it is left in its current state to withstand the projected climate change impacts. The costs of climate change in this scenario are the costs of maintenance and repair to maintain the original design lifespan of the infrastructure. These costs are calculated on an annual basis for each infrastructure element in each grid cell for each climate scenario. Therefore, the total number of cost estimates generated for each year is dependent on the granularity of the spatial analysis, the number of climate scenarios, and the number of assets included in the study. Generalized, this is captured by the following equation:

$$CY = CS * (G * (ST * A)) \quad (2)$$

Where

CY = The number of costs generated per year

CS = The number of climate scenarios under consideration

G = The number of spatial grid cells being analyzed

ST = The number of stressors being analyzed for threshold exceedance

A = The total number of assets

For each scenario where a damage threshold is exceeded, an additional maintenance cost is generated based on a combination of damage severity, maintenance requirement to repair the damage, local cost factors, and productivity of local crews when appropriate.

The functions for estimating the additional maintenance costs differ between each infrastructure type. However, each operates in a similar manner. First, IPSS transfers the general threshold finding to individual assets within each grid. For example, if the temperature threshold is exceeded for asphalt roads, then each mile of asphalt road in that grid must have a maintenance cost associated with it for that year. Second, the specific maintenance cost for that damage is referenced from the cost database on a per mile basis. Given those two pieces of information, IPSS assigns a total reactive maintenance cost for the asphalt roads in that grid cell for that year for that scenario. In general, the cost for the infrastructure in a specific grid in a specific year can be notated as follows:

$$CG = NA * (CM * DL)$$

Where

CG = The total reactive cost in a grid for an individual asset type

NA = Number of assets in a specific grid by measurement (i.e., miles, number of individual assets)

CM = Cost for maintenance on a per threshold level

DL = Damage level of an asset type by thresholds exceeded

As illustrated, each asset type in each grid cell has a distinct reactive cost for each year and each climate scenario. IPSS retains the reactive cost for each year for each asset type in each grid cell to enable aggregation of the totals at the final output stage. In this manner, IPSS can provide a detailed or aggregated total for the reactive costs for any year for any asset for any geographic location.

Secondary Impact Estimation Modules

The impact of projected climate change complicates decision-making from more than just a cost perspective. The disruption to services resulting from increased maintenance or new construction requirements due to adaptation investment will have a broader impact than simply the direct costs of those activities. Additionally, due to uncertainties associated with climate projections, the exact timing and magnitude of extreme events can be difficult to predict. This results in uncertainty over the event and thus creates the potential for overspending on excessive adaptation, underspending due to inadequate adaptation, or underestimating the potential impact by adopting a reactive strategy. This uncertainty requires decision makers to either ignore the potential for climate change impacts or adopt a decision making under uncertainty technique to make an informed decision on a preferred strategy.

IPSS assists in both of these issues through its secondary impact estimation modules. This IPSS component is divided into two general areas, disruption calculation and risk calculation. As each of these are broad fields of study in themselves, the approaches adopted in IPSS represent only one of a number of possibilities for calculating disruptions and risks. However, as with the cost estimation modules, the methods adopted are based on extensive research on methods that have been adopted throughout the infrastructure development community.

Disruption Module

The disruption analysis evaluates the time that an infrastructure element is estimated to be "out of service" either as a result of climate change damage or as a result of additional construction time due to adaptation investment requirements. It relies on historical estimates of the time required to conduct maintenance and rehabilitation activities as derived from commercial sources and global databases such as the World Bank ROCKS Worldwide Database (ROCKS 2021).

The analysis estimates disruption time based on the damage thresholds that are exceeded in each year for each infrastructure asset. For each threshold that is exceeded, the corresponding damage is compared to the database of maintenance requirements to determine the productivity rate for repairing that damage. Given the productivity for a specific damage repair task, the total disruption can be calculated based on the amount of inventory that requires maintenance in a given spatial grid. IPSS provides an additional level of analysis beyond the time of disruption to include an estimated cost of the disruption. Utilizing data definition items provided by the user, such as traffic levels and value per hour of car or truck travel, IPSS determines an estimated cost of disruption for each instance of disruption for an individual asset.

For both cost and duration, the magnitude of the estimate is related to the severity of the damage. Using the threshold exceedance as a basis, the magnitude of disruption is related to the level of threshold exceedance. In this manner, the severity of a damage event is reflected in the level of anticipated disruption. For example, a 100-year flooding event would result in a longer period of disruption compared to a 10-year flooding event because it would likely result in a greater extent of damage. Additionally, the spatial extent of damage and this disruption varies depending on the type of damage. For example, the need for a bridge repair is a localized event versus an increase in pavement cracking due to increased freeze-thaw occurrences. IPSS includes these variances as part of the disruption calculation.

IPSS refines the disruption calculation by differentiating between proactive and reactive disruptions. Proactive disruptions occur due to the time required to implement proactive adaptation measures. These can be minimized through effective scheduling including advanced planning, mobilizing crews and thus minimizing the impact to infrastructure. In contrast, reactive maintenance often occurs due to unforeseen maintenance requirements with little opportunity for planning. This emergency mode of maintenance causes increased levels of disruption as opportunities such as selected closures of roads or bridges may be lost in emergency situations. IPSS reflects this difference by including separate disruption values for reactive and proactive strategies. A key difference between the two strategies is that proactive activities are designed for application only at the beginning of a rehabilitation cycle, and greatly reduce if not eliminate the need for reactive responses during the cycle.

The general formulation for calculating disruption within IPSS is as follows:

$$TD = NA * (TE * DR)$$

Where

TD = Total Disruption for the Assets in a grid

NA = Number of Assets in a spatial grid

TE = Number of threshold exceedances for a specific stressor

DR = Disruption rate per threshold exceedance for a given strategy and asset type

Using this formulation together with the asset inventory provides a total disruption estimate for both the proactive and reactive strategies for a given asset set.

Risk Module

The final module within IPSS prior to the output of results is the risk module, which encompasses both cost and financial risk perspectives. As the concept of risk holds different meaning in different contexts, the concept of risk within IPSS focuses on the underlying uncertainty associated with climate change projections. A challenge in the creation of adaptation strategies is the high level of uncertainty associated with climate change impacts (Dessai et al. 2007; Jones 2000; Schneider 2001). This uncertainty makes it difficult for decision-makers and policy-makers to understand the true nature of the problem and then to choose the best strategy to hedge against future weather events, leading to misinterpretations and misleading decisions about climate adaptation policy (Fankhauser and Soare 2013; Pittock et al. 2001). While uncertainty is a part of routine decision-making, the potential changes in climate pose challenges that lack any historical precedent and are generally unaccounted for in existing policies (Baynham and Stevens 2013; Picketts et al. 2013).

The states of nature, or changes in climate, which may occur in the future carry a deep and severe uncertainty. Deep uncertainty in climate change impact assessments has been a highly discussed topic for almost 20 years among economists, mathematicians and scientists (Fankhauser et al. 1999; Jones 2000; Lempert et al. 2004; Yohe and Neumann 1997). Deep uncertainty describes a scenario when decision-makers cannot agree on the prior probabilities and interdependencies of system model inputs (Lempert et al. 2004). Deep uncertainty can be addressed using "robust decision-making," described as the selection of strategies that produce lower regret as a result of selected actions (Dessai and Hulme 2007; Gupta and Rosenhead 1968). Robust decision-making practices perform better than optimization techniques when probabilities of the state of nature are not well understood (Lempert and Collins 2007; Rosenhead et al. 1972). IPSS thus adopts a combination of robust decision-making techniques as well as cost-benefit analysis and financial portfolio analysis to provide a broad perspective on risk to infrastructure assets.

Cost Risk

Cost risk is the potential difference between taking a reactive and a proactive approach to projected climate impacts. As illustrated in Figure 2, the total cost over the life of an individual asset or a portfolio of assets in terms of climate change impacts differs between climate models (leading to the variance in costs) and climate stressors (leading to different cost originators). Cost risk should therefore be analyzed in terms of the underlying stressors that lead to the risk, the variance in the projections, and the difference between the proactive and reactive strategies.

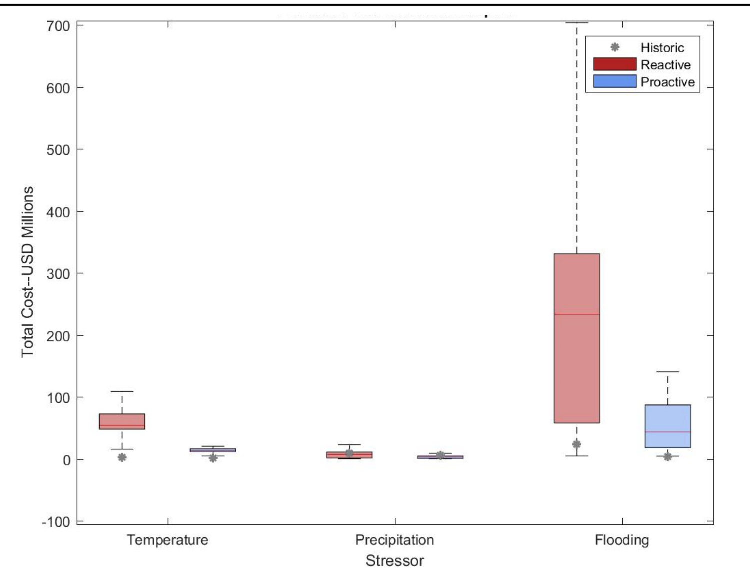


Figure 2: Proactive and Reactive Boxplot

As illustrated in this example, each of the three stressors creates a different set of decision-making considerations for this portfolio. Addressing temperature-related impacts proactively reduces variance and costs compared to a reactive approach. The precipitation stressor results in smaller impacts than temperature or flooding, and addressing precipitation-related impacts proactively reduces both variance and costs compared to a reactive approach, although the reduction is notably less than in the case of temperature. Finally, addressing the flooding stressor proactively results in a significant reduction in variance and cost, but this stressor causes the greatest potential cost for either strategy when compared to the other stressors. In this case, if limited funds are available, a decision needs to be made regarding which strategy and which impacts may be the preferred focus for an investment.

For an overall perspective, costs can be compared for individual models or groups of models on an annual, decadal, or cumulative basis. As illustrated in Figure 3, reactive and proactive adaptation strategies will differ in their results depending on the strategy used, the scenarios selected, the assets being analyzed, and the impact of the individual stressors. As illustrated in this example, the cumulative difference between the proactive and reactive strategies amounts to over $200 million. The difference being evident from the 2030 decade onward with the average annual difference in cost in the 2030 decade being $4.5 million ($45 million over the decade). By the 2060 decade, the average cost difference increases to $5 million annually. This difference represents the cost risk to the decision maker as to the potential underspending that may occur due to a decision to adopt a reactive strategy rather than a proactive strategy.

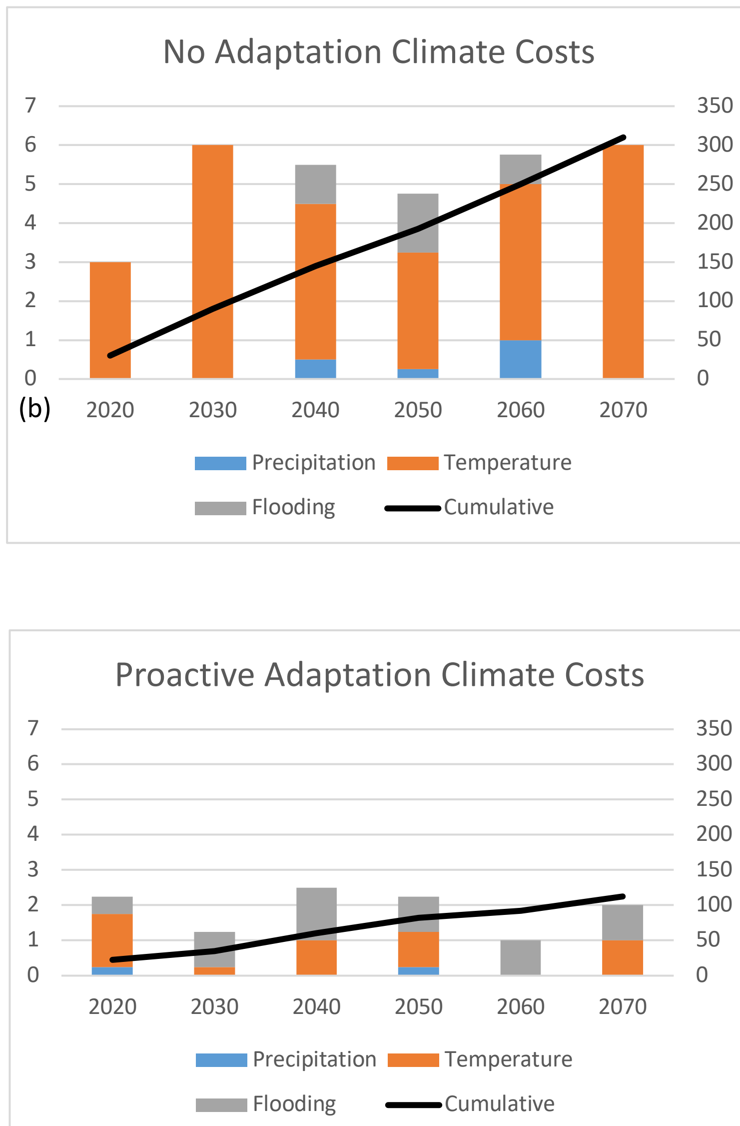


Figure 3: Example of No Adaptation and Proactive Adaptation costs accumulating by decade.

Regret Risk

The difference between investing in adaptation or waiting to determine the increased maintenance costs is the cost risk for an individual outcome for a climate scenario. However, climate projections extend across a suite of climate scenarios. Within IPSS, this suite includes 42 scenarios plus a historic scenario. Given this range of potential outcomes, together with the deep uncertainty and lack of probability that is accepted with each scenario, the potential exists for any climate scenario to be the actual condition under which the infrastructure will operate. When the actual scenario is different from that upon which an adaptation strategy is based, the potential exists for either overspending (investing too much in adaptation compared to what is actually required) or underspending (investing too little in adaptation or adopting a reactive strategy versus what is actually required). In both of these scenarios, there exists a “regret” of incorrectly estimating the cost required to address climate change impacts.

IPSS can evaluate the potential risk of regret by calculating the potential difference in the costs associated with each climate scenario. This results in over 1,600 different combinations for every climate stressor in every analysis. When combined with each of the possible strategies that can be employed for each stressor, the number of options multiplies exponentially within the system. However, to aid in decision-making, IPSS provides the user with a frequency analysis to provide a statistical depiction of the likelihood of regret for a given set of portfolio assets (Figure 4). In this depiction, the user can see whether there is significant agreement between the scenarios in terms of potential impacts (a small dispersion across the histogram) or if there is little agreement regarding the outcomes (wide dispersion across the histogram).

IPSS uses the dispersion of regret outcomes to provide insight into whether regret is isolated to a narrow band of outcomes or may have a broad set of outcomes. In the case of a narrow dispersion range, the decision maker is presented with a decision as to whether this outcome has acceptable risk or whether greater investment is required to minimize the regret potential. In the broader dispersion, the decision-maker is presented with a problem that may require greater investigation since a clear answer is less apparent. In this case, additional risk analysis that includes broader financial measures may be required.

Financial Risk

The last risk perspective in the IPSS system centers on financial risk. Building on portfolio analysis and cost-benefit analysis concepts, IPSS calculates financial measures that extend risk beyond the common regret perspective. Specifically, IPSS calculates a variance risk, a valuation risk, and a breakeven analysis to assist the decision-maker to implement a broader decision process.

Variance risk arises from the portfolio concern that the greater the variance in performance over time, the greater the risk associated with an investment (Boundless 2017). For climate impacts, this risk and variance is related by IPSS to the total costs associated with climate on an asset or group of assets. Utilizing a five-year average, the optimized cost of climate impact (calculated as the least cost option between proactive and reactive strategies for each asset), is calculated for each climate scenario. Analyzing this variance over the life of the study enables IPSS to present the financial risk in terms of the amount of increase (or decrease) in cost variance that the asset(s) incur over the life of the study. Where variance is seen to increase past an accepted level of risk, the decision-makers may elect to explore new alternatives to reduce the climate risk exposure.

Valuation risk places projected climate cost impacts in terms of the replacement value of the asset(s). In this perspective, each asset or group of assets are analyzed in terms of the reduction in valuation of the assets based on their exposure to projected climate costs. This analysis reflects two elements from the previous cost analysis, variance and total value. In terms of variance, the greater the span of outcomes from the climate models, the greater the potential outcome will be in affecting the valuation risk to the asset. In terms of total value, the analysis presents the user with the potential total reduction in value that can occur to the asset based on the multiple climate scenarios. In scenarios where the total value is "high" and the variance is narrow, the asset can be considered at high risk to its valuation.

Finally, breakeven analysis provides an analysis based on climate impact costs and disruption values how many days of disruption savings must be obtained to make a proactive investment cost effective. This case is specifically for instances where proactive strategies cost more than reactive strategies. In this instance, the decision maker must believe that the additional cost has value in terms of reducing the disruption days for the user base. For example, if the cost difference between the proactive and reactive strategies is an additional $100,000, but a proactive strategy reduces the number of disruption days by 50, then the question is whether each day of reduced disruption is worth at least $2,000. If the value of the reduced days is worth at least this amount, then the proactive investment exceeds the breakeven point. However, if the value of these days is less than the $2,000 amount, then the breakeven is not obtained and a secondary impact must be considered to approve the additional investment.

The combination of these perspectives provides the decision-maker with a second set of information on which to base a decision. Rather than limiting the focus to costs, the financial risk perspectives allow a decision that incorporates risk to the value of the asset itself as well as the potential return on the investment. From this additional perspective, IPSS permits decision-makers to move from an operational perspective to a strategic planning perspective.

Output Module

The final IPSS module focuses on creating output from the large dataset created during the analysis process. IPSS provides flexibility in the output process based on the use of the spatial grid and individual assets as underlying data references depending on the analysis mode. Utilizing the grid as a reference point, IPSS can generate output at any spatial resolution from individual grid cells through national summaries. This spatial resolution can then be differentiated based on the types of assets within that spatial resolution. Complementing the spatial grid is the storage of information at the individual asset level. Through this data reference point, IPSS can output information for any asset individually from any point in the analysis process. Once again, this information can be aggregated to show portfolio-level results for any group of assets.

Figures 4 and 5 provide examples of this difference between individual and portfolio-level output with Figure 4 illustrating risk information being aggregated for four assets for the variance analysis and Figure 5 illustrating the four assets separated for the valuation risk analysis.

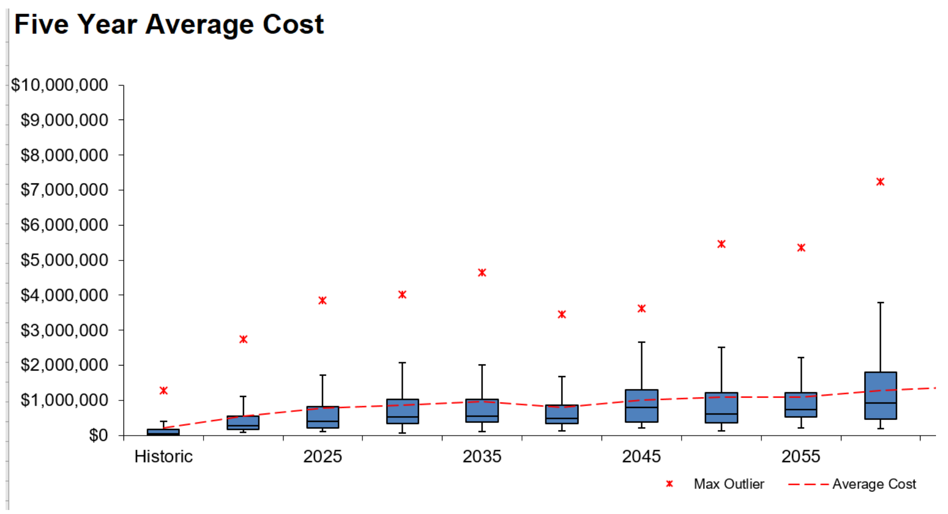


Figure 4: An aggregated portfolio view of cost variance over time illustrating cost risk for four assets.

IPSS automatically generates a suite of overview graphics for each analysis run covering all phases of the analysis process including; climate summaries, cost impacts for both strategies plus comparisons over the full analysis period, cost profiles based on climate stressors for representative climate scenarios, risk graphics for cost, valuation, and regret analyses, and summary spreadsheets. Additional graphics can be developed based on user needs. Additionally, mapping data is generated by IPSS as needed to facilitate GIS visualizations of IPSS-generated output (Figure 6).

In summary, IPSS provides support for a broad array of output options. Standard options include both graphic and quantitative outputs. However, IPSS is customizable to generate data to support almost any form of cost or risk analysis.

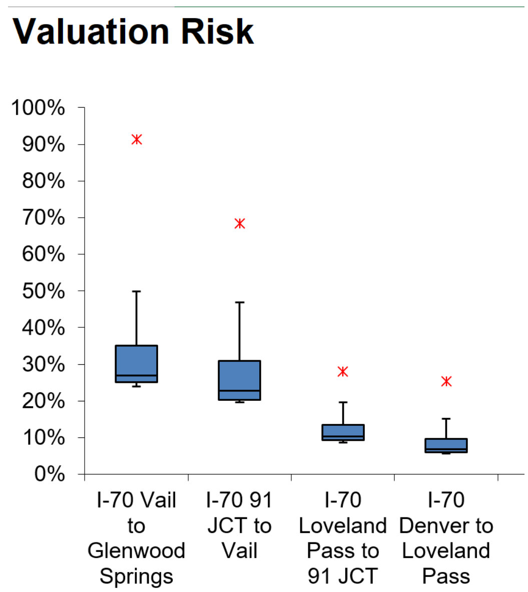


Figure 5: An individual asset view of valuation risk associated with specific assets in an overall portfolio.

Scenario Planning

The uncertainty associated with climate change impacts necessitates that decision-making take into account multiple scenarios for approaching climate adaptation. IPSS facilitates this process by supporting multiple scenario generation. Utilizing a multi-scenario framework, a user can start with a default analysis that utilizes built-in costs and adaptation methods. The user can then customize the analysis by changing any combination of costs, default or custom adaptations, and assets included in the analysis. As IPSS is optimized to run an analysis in under 30 minutes, multiple scenarios can be generated in a single day using all climate scenarios and all user-selected customizations.

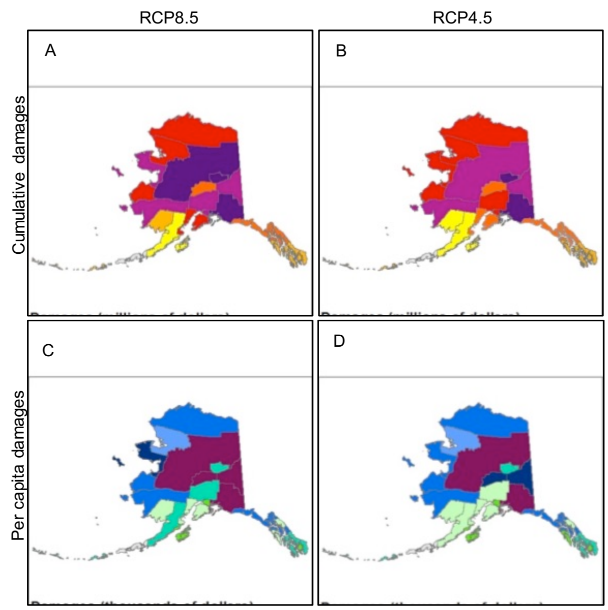


Figure 6: IPSS can generate data to support mapping of asset or portfolio risks in spatial boundaries. From Melvin et al. 2017.

The difference that IPSS brings to climate impact analysis is based on scenario planning. Rather than limiting analysis to a handful of climate scenarios or a selected set of stressors and a limited vulnerability perspective, IPSS provides decision-makers with the broadest set of data available. This “big data” approach allows decision-makers to obtain as complete a picture as required to make an informed decision. In some cases, this may take only a few runs, in others this may be dozens that explore multiple adaptation options, multiple asset portfolios, and multiple discount and inflation explorations. Enabling this complete set of perspectives is the foundation of the IPSS approach.

Key Limitations

Although IPSS is designed to be flexible and robust, there are limitations to the system based on the approach underlying the system analytics. The primary limitation is that IPSS addresses climate impacts through discrete time-steps. In this methodology, IPSS determines impacts on an annual basis and assumes that the percentage of assets that can be maintained on an annual basis are actually maintained. In other words, IPSS assumes that any damages incurred are addressed in the year which they occur. Additionally, investments in resiliency are assumed to be accomplished in the year in which they are undertaken and are not carry forward as uncompleted tasks. The resulting limitation from these assumptions is that disruptions and investments for a single infrastructure element are not carried over multiple years which may actually occur in real-life situations.

In addition to the discrete time steps, IPSS addresses assets and stressor impacts separately. While the concept of network interdependencies and interactions are being designed in the IPSS system for future consideration, currently all damages are treated independently through the threshold process. In this perspective, IPSS does not incorporate network relationships between assets. The resulting limitation is that IPSS does modify the estimated damages to assets resulting from interdependencies within a network.

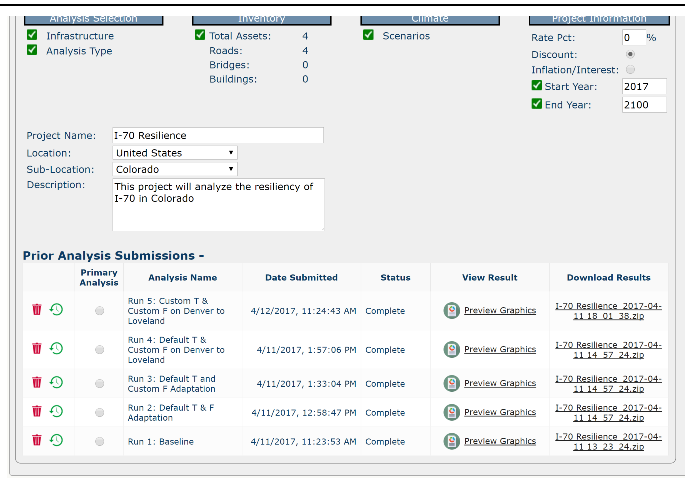


Figure 7: IPSS supports multiple scenarios by allowing incremental changes to cost, adaptation, and asset inclusion in an analysis run.

Finally, IPSS is limited by its assumption that maintenance of assets occurs on a regular basis. This limitation is based on the assumption that asset owners prefer to have an asset retain a design lifespan and thus will conduct maintenance accordingly. However, this assumption can be overridden in IPSS's cost and adaptation settings.

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