# 5.0 SYSTEM VULNERABILITY MODELING

## 5.1 Introduction

This chapter deals with the shaded box in Figure 1 that reads "Estimate System Performance (Loss of Service, Environmental Impacts, Higher Order Losses)." In the next chapter, there are demonstration examples of how a system evaluation can be made.

Essential to the evaluation of system performance is a system vulnerability model. In such a system vulnerability model, the basic issues to be addressed are whether nor not the final nodes (service zones, service connections, fire hydrants) have (a) flows with adequate fire flow and pressures or (b) potable water supply that meets stringent safe drinking water health standards.

This chapter will begin with a brief discussion of the types of system losses or adverse consequences on interest in a system risk evaluation. (section 5.2) The remainder of this chapter will focus first on modeling the post-disaster reconstruction process (section 5.3), simplified graphical and connectivity modeling (section 5.4), and hydraulic modeling (section 5.5).

## 5.2 System Losses Estimated Based on System Vulnerability Modeling

System losses after natural disasters can be interpreted in many ways. For instance, one can evaluate the numbers and durations of service zones lacking adequate fire flow pressures and/or lacking sanitary potable water supply. One can further identify those service zones that are more susceptible to water outages and/or shortages after natural disasters. In addition, there are extra costs required to respond to and recover from the natural disaster.

One can further translate these water outages and/or shortages and extra costs into various economic terms. One such translation is in terms of prospective revenue losses to the water utility itself. These will be a function of rates and reduced water deliveries as these apply to different customers within the system as well as extra costs to respond to the system damages. Some of these revenue losses will be over and above the repair and labor costs that the water utility system itself incurs after governmental disaster assistance moneys, if any, are received.

Another such translation is to develop estimates of losses to the customers themselves. For instance, specific commercial, industrial, or institutional customers may have fairly well-defined water needs and may know fairly well the types of business or productivity losses that would arise from various water outages and/or shortages of various durations. In general, a business or economic survey would be needed to develop models of business and/or productivity losses arising from possible water outages and/or shortages.

Higher-order loss estimation, over and above primary losses and business interruption losses, is beyond the scope of this document. Nonetheless, macro-economic models exist that can estimate how much overall impact primary losses and business interruption losses can have on the local and regional economies. Such models generally need to take into account the infusion of outside capital (such as disaster assistance moneys), how productivity losses at one location can be compensated for by productivity gains at another location, how well business owners can shift their businesses in order to survive and possibly thrive in circumstances that have changed after the disaster, how some businesses such as utility construction firms may have increased business after disasters, and how various businesses are dependent on those that have suffered primary losses (e.g., how the tourist industry is dependent on local motels and hotels, that may have suffered losses owing to water outages and/or shortages).

## 5.3 The Reconstruction Process

A first look at water system risks will evaluate how the water utility system is expected to perform immediately after a natural disaster. However, this look will not give a very full account of the system losses expected. This is because instantaneous water shortages and outages have very little impact except in rare cases. If a quantitative account of prospective system losses is desirable, then the system must be modeled at various time-periods after the postulated natural disaster event. For instance, in a very severe disaster, it may take days or weeks or even months for the water utility system to be fully recovered. The basic concern in estimating system losses is for the duration and type of disruption to the water system from natural disasters.

System states at time-periods after the natural disaster can be more challenging to model than system states immediately after the disaster. This is because modeling the restoration processes for water systems could involve consideration of such factors as:

- times to repair diverse components with various damages (e.g., times to repair a leak, to repair a pipeline break, to disinfect a service zone)
- prioritization of repairs and restoration activities (e.g., easy repairs first, main trunk lines next, restoration rapid for emergency operation facilities, hospitals, and other critical facilities)
- effectiveness of mutual-aid agreements
- availability of qualified repair crews (e.g, does the disaster-affected region contain a boom in available labor and is this labor qualified to assist in the process, and do mutual-aid workers arrive in time, and how long do they stay?)
- use of utility contractors
- effectiveness of initial damage surveys
- functioning of communications systems
- access to damaged facilities (e.g., vehicle access, roadway access, safety of entering a locale)
- technology used to assess damage and make repairs (e.g., how do newer technologies accelerate the repair process and/or create more resistant facilities after the process is over)
- spare parts

- adequacy of equipment available
- the use of SCADA and other control and/or monitoring systems
- coordination with wastewater, building and safety, electric power, natural gas, fire services, and other agencies
- response to public including media concerns
- governmental policies on outside resources provided, mitigation, reimbursement for disaster response and recovery activities, safety, security, and health.
- The reasonableness and fortuitousness of actions taken in the midst of a disaster (e.g., mistakes made while responding in a crisis or the sub-optimality of actual water system restoration processes; challenging decisions such as to whether a distribution storage tank should be allowed to be drained in order to maintain adequate fire flows)

There is not likely to be a simple restoration model that can cover all such factors. (See Lund, 1991, Lund, 1999, Matsushita, 1999, Ballantyne, 1995) Restoration modeling for natural disasters currently requires considerable research. (See Chang, Shinozuka, and Svelka, 1999)

Still, there are various ways to approach modeling the restoration process so that a helpful assessment of water system losses can be made. These involve:

1. an assessment of how long it would take to repair various system components (including an assessment of the labor required for such repairs);
2. an assessment of the prospective availability of labor, equipment, financing, and spare parts needed to make repairs, including labor, equipment, and spare parts through mutual-aid agreements and state and federal assistance;
3. a preliminary assessment of the priorities within the system should a large-scale disaster take place (e.g., should prospective labor, equipment, financing, and spare parts not permit all damaged components to be repaired at the same time, or should repairs be required to proceed in an orderly fashion in spite of an abundance of labor, equipment, and spare parts and what temporary repairs should be made);
4. assumptions on (and/or evaluations of) how the water utility will fare with respect to other infrastructure systems (e.g., firefighting, communications, wastewater, electric power, natural gas, petroleum, transportation);
5. assumptions on health-related field monitoring and how the system will be disinfected (as needed) once repairs are made to assure that water quality standards are met and how long this disinfection process will take before a fully repaired system can serve potable water.

The minimum amount of time to restore a system thus includes time for a damage survey, time to locate and mobilize repair crews, equipment, and supplies, time for repairs to be made, and time to disinfect the system.

With limited resources, priorities need to be set on which portions of the disrupted water utility system should be repaired and restored. The following steps could be modeled in a water system restoration process that suffers from limited resources—resources that will not permit all repairs to be made simultaneously:

1. Before the disaster, an emergency water supply plan is developed as part of the utility's emergency response and recovery plan. This emergency water supply plan includes the designation of responsibilities, communications capabilities, mutual-aid agreements, planned cooperative efforts with other agencies (e.g., the Corps of Engineers, FEMA, state disaster management agencies, state health agencies), and potential operational strategies for restoring the water system. (Note that the American Water Works Association document *Emergency Planning for Water Utilities*, M19, provides a manual of water supply practices.)

2. Once the disaster occurs, a field damage survey is needed to be undertaken. This field survey will include not only the identification of malfunctioning water components, but also special facilities and/or service zones that are specially suffering from lack of water supply. For instance, the presence of fires in one locale will point to special needs for the water supply system. Customer communications and SCADA system data are among further supplements to field damage survey results.

3. Based on this field survey, a strategic approach to restoring the system needs to be undertaken. This strategic approach will require adequate coordination, communication, transportation, and safe and healthful execution. Priorities in service restoration need to be set. For instance, according to AWWA-M19, most medical facilities need continuous service. Likewise, emergency operations facilities including fire and police departments will be prioritized highly for service continuity and restoration.

4. As a primary step in this strategic approach, water supply and transmission components, including pumping stations, will need to be restored—at least enough to provide immediate water supply needs.

5. At the same time, major leak sources should be isolated by closing valves. This is required in order to reduce water losses and also to avoid possible contamination sources from affecting the piping. In some cases, however, some pipelines may be allowed temporarily to leak because these pipelines are needed for adequate fire flows. These pipelines may be repaired at a later date, such as during the night, after flow demands have subsided.

6. Distribution piping should be strategically repaired in order to service higher priority service zones and locations. This will involve identification of how flows can best be transported to these service zones and/or high-priority facilities.

7. Repairs of all damaged and necessary components should be completed after these immediate strategic steps.

8. Throughout, water quality should be monitored, and special disinfection should be applied to assure water quality. Coordination with other infrastructure systems and health officials should assure that contamination effects are removed.

9. The entire system is restored once all service zones achieve pre-disaster flow capabilities meeting stringent health standards.

Modeling all of these steps could yield a very complex model. Optimizing prospective emergency response activities could be one of the uses of an evaluation of system risks to water utilities threatened by natural disasters. Actual response to a natural disaster is virtually always expected to be somewhat sub-optimal. Sources of sub-optimal post-disaster restoration are numerous: personnel may be unavailable; there may be airborne hazards (e.g., chlorine leaks) or waterborne hazards; roadways may be impassable; communications may be disrupted; unexpected or undetected damages may have occurred; water utility vehicles may be damaged or otherwise dysfunctional; unexpected demand surges such as from leaking pipes or damaged sprinkler systems may lead to precipitous pressure reductions.

However, in spite of such limitations of any restoration model, if the assumptions of such a model are well-understood, then it can be useful in developing system states at various times after a postulated natural disaster so that system losses can be estimated.

## 5.4 Simplified Graphics and Connectivity Models to Evaluate System States

### 5.4.1 Circumstances Under Which A Hydraulic Evaluation May Not Be Needed

Once system states are identified, they can be evaluated in fairly simple terms as in this sub-section or through the use of hydraulic evaluations in the next section (5.5) However, hydraulic evaluations may not be absolutely essential. Under some circumstances, a much simpler systems approach may be adequate. These are here defined as:

- The system is basically a simple gravity flow network
- The pertinent portion of the system is basically a gravity system
- The pertinent portion of the system is so linear that hydraulic issues (e.g., which customers would not be served given various system failures) are known in advance

As a first instance, Figure 33 outlines a simple gravity flow network. Except for the wells that require booster pumps, the flows in Figure 33 generally follow gravity. By and large, then, loss of functionality upstream in the system will lead to loss of water in the downstream service area.

As two additional instances, the decision in question may pertain to a facility or sub-system that can be isolated from the rest of the system.

First, in Figure 33, the decision in question may pertain either to the source of supply or to a water treatment plant. Based on vulnerability and natural hazard models for the water treatment plant, one may discover, for instance, that natural hazard events affecting this water treatment plant will cause it to be out-of-service for an average of one day per year, with a maximum estimate of thirty days of downtime. One can further determine that if the water treatment plant is out of service for one day, then revenue losses are $D. This information may be used to assist in determining whether or not additional water supplies are needed for the system. In such an evaluation, the rest of the system is ignored owing to the criticality of the water treatment plant within the system defined in Figure 33. A simplified evaluation may be adequate for the decision at hand.

Second, in most systems, one might isolate the “pump-tank” system for purposes of evaluating whether or not additional water distribution storage is needed in a specific local. The “pump-tank” system consists of a single booster pump station that provides water flows to a distribution storage facility, which in turn serves a single service zone or locale. No other booster pumping station or distribution reservoir serves the locale. Thus, there is a critical non-redundancy in the locale in question. For deciding whether or not additional booster pump stations and/or distribution reservoirs and/or interconnection to another service zone system should be constructed, one may treat only the “pump-tank” system in isolation from the rest of the system. This “pump-tank” system may be treated very simply, without the need for special hydraulic evaluations (which would nonetheless be used in the design of any booster pump stations and/or siting of any water distribution reservoirs). Revenue losses associated with the pump-tank system can be estimated based on revenues from the locale isolated for evaluation.

In all these cases, the criticality of components and their potential downtime serve as reasons to provide simplified evaluations. The more non-redundant components can sometimes be isolated from the rest of the system. Those non-redundant components that have long potential downtimes as a consequence of natural hazard events deserve special attention in natural hazard risk-reduction decision-making.

### 5.4.2 Graphics and Connectivity Evaluations For System States

For simplified evaluations, a graphical portrayal of the system such as in Figure 33 can be adequate. From such a graphical evaluation, one can analyze the system into combinations of two kinds of sub-systems as in Figure 34.

Series or linear systems are those that have no redundancy (See Figure 34(b)). There is only one pathway from Source S1 to demand node D. That pathway is through links A and B, respectively. Parallel (redundant) systems are those that have at least multiple pathways and possibly multiple sources (see Figure 34(a) for an example).

The series and parallel systems shown in Figure 34 can be used to illustrate the extreme importance of redundancy. Let us suppose that for a specific natural hazard event, one estimates that the probability of failure of link A is 0.2 and the probability of failure of link B is 0.3. (This assumes that the component vulnerability models used do not merely yield binary results, that is, success or failure.) One could use these probability arguments to simulate a large number of system states in order to estimate the probability that demand node D will be served by source S1. However, for the very simple systems shown in Figures 33, simple calculations are adequate.

For the series system, one derives a probability of water outage of 0.44 at demand node D. (See the formula shown in Figure 34(b). In sharp contrast, for the parallel system, one derives a probability of water outage of 0.06 at demand node D. Thus, for the natural hazard event hypothesized, the parallel or redundant system has a far greater chance of serving the demand node.

For a small number of links and nodes, one can readily use such formula for each of the natural hazard events simulated. However, the situation becomes more complex if the evaluation contains a great many links and nodes. At some point, it may even be prudent to include a hydraulic analysis inasmuch as the evaluation efforts are not much greater than performing a connectivity evaluation.

Appendix E contains a preliminary characterization of how to evaluate quantitatively a connectivity or reachability evaluation. Appendix E also contains methods for developing prior estimates of component importance based either on a connectivity or a hydraulic evaluation.

## 5.5 Hydraulic Evaluation

### 5.5.1 Introduction

Water supply and distribution systems response to one or more natural hazards determines its ability or risk as a system to respond and provide the needed services from when the natural hazard event occurred through restoration of the facilities. A water system as compared to a specific component must be viewed and evaluated based on all components that comprise the water distribution system. Therefore, a water distribution system hydraulic model needs to be the primary tool in assessing the systems ability to respond to natural hazards.

### 5.5.2 Basics of Hydraulic Systems Evaluation

Large and some medium size water supply and distribution systems have incorporated hydraulic models to evaluate their particular systems ability to meet hydraulic requirements including existing and future water needs (i.e. fire flow, maximum day or MD and maximum hour or MH domestic needs, storage needs, etc) and to properly size future facilities. The hydraulic models currently utilize similar water system component(s) physical parameters (i.e. pipe size, pipe lengths, node elevations, storage tank overflow elevations, etc.). There are a number of standards developed to support the water utility in the development and execution of water system modeling including AWWA M32 - Distribution Network Analysis for Water Utilities, and AWWA M31 – Distribution System Requirements for Fire Protection. Physical information can be obtained on a particular water system from existing reports, construction drawings, USGS topography maps, GIS information and supplemented by field surveys. The hydraulic model for the purpose of this study should focus on the water supply and distributions “backbone” systems.

Natural hazards can occur over a large geographic area and/or in site-specific areas (i.e. drainage crossing). A screening approach must be considered in determining the critical natural hazards that could disrupt both domestic and fire flow services. The water system “backbone” is considered to be the most critical pipelines because of their function to deliver large quantities of water to specific service areas. Therefore, the backbone system at their relative locations/crossings of potential natural hazards needs to be reviewed. The highest priority should be given to those natural hazards that have the highest potential for occurring within the geographic region.

### 5.5.3 Natural Hazard Conditions

During a natural hazard event, the water system ability to respond may vary depending upon different water system operating conditions (pre-natural hazard event, post natural hazard event, water system restoration, and startup). Based on a steady state hydraulic analysis, the above four water system operating conditions should be modeled to determine the water systems vulnerability to the natural hazard. However, the modeler should review the need for an Extended Period Simulation evaluation if terminal water storage tanks are impacted in order to assess the water system ability to meet MH and fire flow needs. The water system operating conditions are further defined below;

- Pre-Natural Hazard Water System Condition – The hydraulic model would reflect the water supply and distribution system(s) existing steady state operating condition prior to the natural hazard. The model would reflect current water system hydraulic requirements including fire flow requirements and would provide a base line for the subsequent modeling of conditions/events that would occur. A very random approach to this pre-natural hazard water system condition would consider randomly the expected demand on any day of the year, and so include various seasonal and other effects on demands.
- Post Natural Hazard Water System Condition – The hydraulic model would reflect the steady state operating conditions of the water system component(s) immediately following a specific natural hazard. This event is anticipated to reflect a reduction or elimination of water system component(s) ability to meet fire flow and/or domestic water needs as defined above.
- Water System Restoration – The hydraulic model would reflect the steady state operating condition of the water system component(s) during restoration of water component(s) that were damaged during the natural hazard event. This may require some components to be shut down in order to allow for restoration and could cause a greater impact on the water system.
- Water System Start Up Condition – The hydraulic model would reflect the steady state operating condition of the water system component(s) once the system component(s) have been restored. In certain cases, upgrades to the water system may have occurred that would reflect an improved steady state operating condition from the Pre-Natural Hazard water system condition. In other cases, some services may no longer be required because facilities have been damaged or otherwise no longer require water delivery.

### 5.5.4 Adjustments for Natural Hazard Conditions

The hydraulic modeling of post natural hazard water system conditions that reflect the true impact to the water system component(s) will be primarily based on the specific hydraulic model being utilized. The modeling of water system components that have completely failed are fairly straight forward and would in essence, remove/shutdown those facility(ies) (i.e. severe pipe break) from the model. However, the modeling of those facilities that have been damaged and are partially functional begins to place engineering judgement on how such damage would be replicated in the model. The following are a few examples that may be considered in developing the post natural hazard water distribution system condition.

- Complete Pipe break – The pipeline modeled at the break would be either a fixed grade node or a demand would be placed near the break and would reflect the amount of flow. The model would reflect the pipe as closed during repairs and restoration of the line.
- Partial Pipe Break – The pipeline would be modeled with additional demands along the segment to reflect the amount of leakage occurring. The model would reflect the pipe as closed during repairs and restoration of the line.
- Tank failure – The pipe to the tank would be closed.
- Partial Tank Failure – The fixed grade node elevation would be lowered to reflect the new operating level. However, during restoration, the tank may be removed from service and therefore the pipe to the tank would be closed. In a steady state model, the reservoir overflow level is lowered to reflect the interim operating level. In an extended period simulation, the tank level diurnal curve is adjusted to reflect partial tank failure.
- Pump Station Failure – The pump station would be shut down (i.e. the pumping units would be modeled as closed). During restoration, the model will reflect pumps coming back on line depending upon the extent of damage to the respective pumps..
- Partial Pump Station Failure – The pump station pumping units that are damaged would be remove from service and therefore reflect a pump station with reduced pumping capacity. Removing the damaged pumps from operation and thereby reducing the total pumping capacity will reflect this.

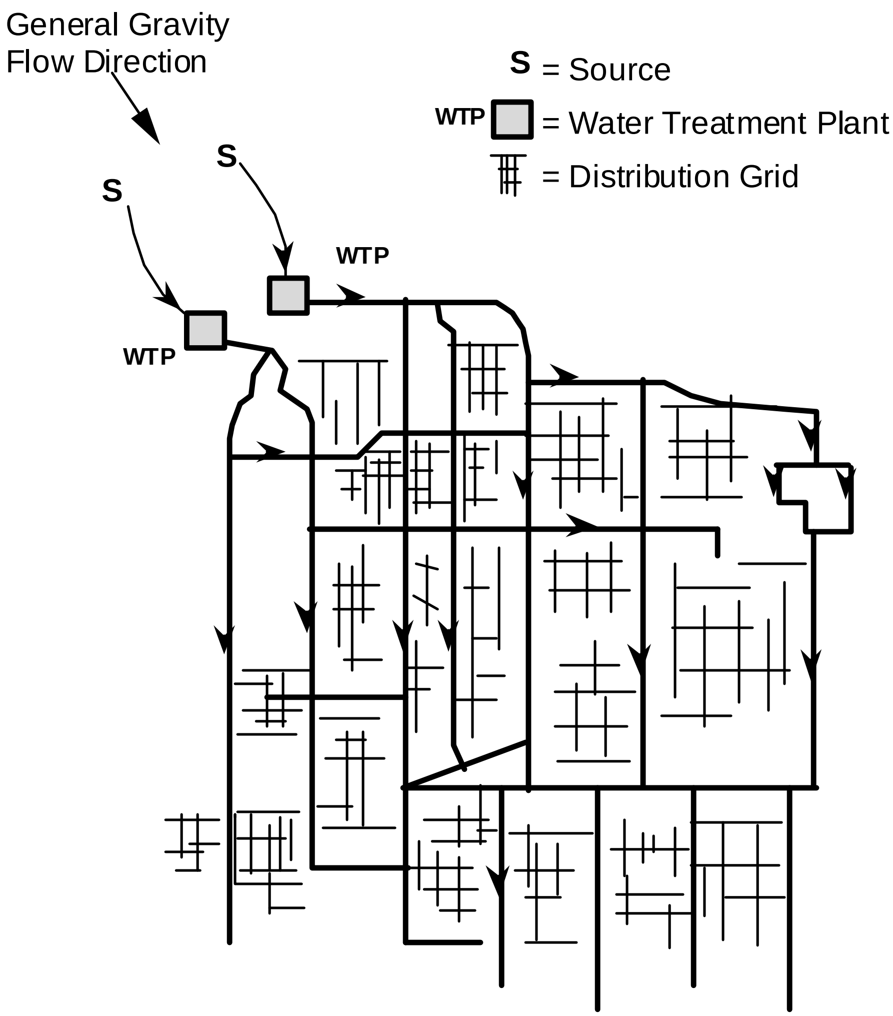


*Figure 33: Outline of Gravity Flow Water Network*

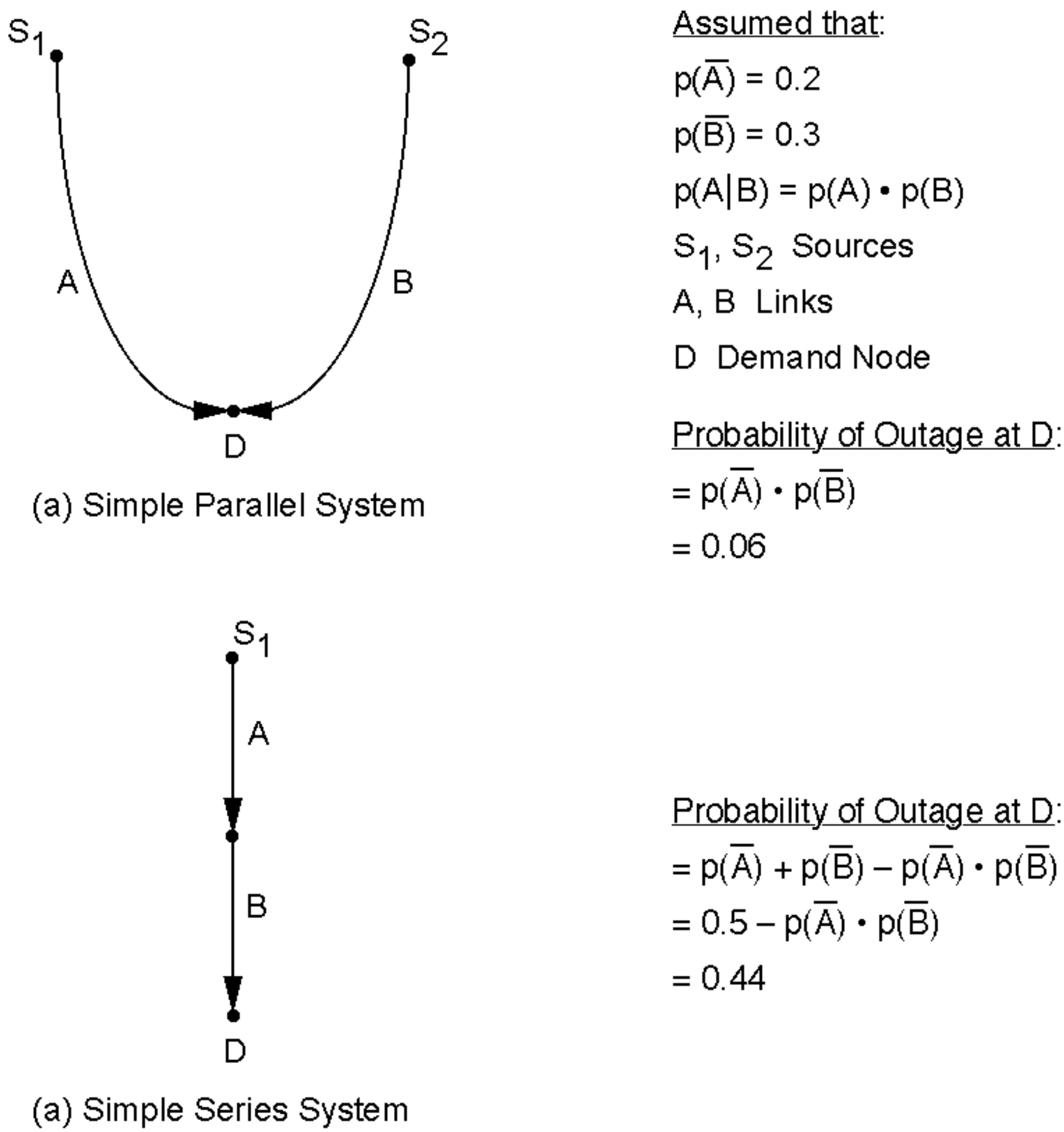


*Figure 34: Two Simple Systems Illustrating Need for System Analysis*