**Collaborative Science and Adaptive Management Program (CSAMP)/Collaborative Adaptive Management Team (CAMT)**

**Identification and Prioritization of Gaps in the Current Understanding of the Water Project-Linked Effects on Juvenile Salmonid Survival in the South Delta**

**Response to Review Questions (additional comments are provided on an annotated document)**

1. Is the outlined approach sound and reasonable to ensure objective, transparent and comprehensive review of the state of the science regarding water project-linked effects on juvenile salmonid survival in the South Delta?
    - The approach here is somewhat confusing for those more familiar with the DRERIP approach. In DRERIP the conceptual models were designed to consider multiple factors influencing 'ecosystem attributes'. The evaluation process developed for DRERIP (that included the consideration and magnitude, certainty, etc.) was a process designed to use the conceptual models to evaluate actions. Here you seem to be developing conceptual models to develop specific actions. This results in several issues/points of confusion (for this reviewer):
        i. There is no way of seeing the effect of an action relative to the rest of the things that influence the ecosystem attribute (salmon population). In the description of the process (end of page 2) it states that linkages not relevant to SST scope are set aside. It seems that the 'ultimate magnitude' consideration really needs a broader scope of consideration – and without a real process/CM that shows that you will end up leaning back on a potentially selective/biased interpretation of knowledge rather than the transparent, objective process you are trying to achieve.
        ii. The rationale for the selection of the linkages is opaque unless placed in the broader context of the species population dynamics. Maybe this is too obvious for this purpose and that all the readers/users of the process are exactly on the same page about how south Delta survival fits into overall recovery/population. Is this a well-documented bottleneck? A bit of upfront text would be helpful and make this more of a standalone science process that a court-ordered mandate – and thus is becomes more useful in other contexts.
    - It is possible that the examples are not yet fully fleshed out but there is a lot of use of vague terminology (see detailed comments on the document) and a lack of citation for what appear to be quite important statements. If you seek to be objective, transparent and comprehensive then it is probably impossible to also be time limited (8 hours) and space constrained. These might need to be long documents and a table format might not work. As the citations in the tables were not listed in the document provided it was impossible to evaluate whether a comprehensive approach was taken to information sources and whether or not they were appropriately used against the criteria shown in Pahe 1.3 (on page 4).

2. Is the process likely to succeed in documenting scientifically well supported linkages, describing key scientific uncertainties and identifying research gaps? Will it support collaborative science?
    - One of the concepts included in the DRERIP process that seems to have been removed here is that of 'predictability'. A process can be well understood in terms of its

mechanics but unpredictable because it is highly variable in nature, and or dependent on specific combinations of conditions. That would be fine but on page 3 '*It is expected that linkages with strong scientific support regarding a large effect on survival of Central Valley salmonids in the Delta will support either short-term or long-term management actions to* ***predictably*** *alter that effect and therefore will not require additional analysis or investigation*' implies that 'predictability' is an expected use of the process. How does this play in – or not?

- The document seems to assume that all gaps that are identified can be filled by 'research'. That may not be the case and/or 'filling the gap' may not be tractable due to time/resource constraints. This needs to be acknowledged and the process needs to identify how decisions about what to try and fill and what not to try and fill will be made. For example, a 20 year record of data may be needed to fill some gaps – and thus the gap cannot be filled for decades even if the work was initiated? Some may require a scale of investment (in terms of time, $$, water, personnel, etc.) which is not considered reasonable? Not all uncertainties surrounding management decisions can be reduced by research – even collaborative research. It would seem important that this process results in a tractable research agenda – including an element in the process that specifically speaks to what is tractable and what isn't would probably be helpful so as to ensure all participants have equal expectations in that regard.

3. What are the key areas of research team's technical expertise that would be essential for the successful completion of the proposed work?
    - No work is currently proposed so this is difficult to answer. Also this reviewer is not an SME in this type of ecological research.

4. Are there some novel ways the research team should consider for presenting the results?
    - Given that the tabular approach may be limiting if the evaluation seeks to be comprehensive (see previous comment) a set of hyperlinked sheets/documents would seem to be more useful than a 'flat' pdf-type report. This could include links to the actual publications/reports cited to ensure ease of access to all the information thus increasing transparency.

**Identification and Prioritization of Gaps in the Current Understanding of Water Project-Linked Effects on Juvenile Salmonid Survival in the South Delta (Salmonid Scoping Team Work Plan Element 1)**

**CAMT Salmonid Scoping Team**

**July 14, 2014**

## Introduction and Purpose

The purpose of this project is to collaboratively identify and evaluate driver-linkage-outcomes regarding water project–linked effects on factors affecting salmonid survival in the south Delta. The water project-linked effects on salmonid survival are defined in the scope of the CAMT Salmonid Scoping Team (SST). The objectives are to document scientifically well supported linkages in the conceptual models, highlight key scientific uncertainties, and prioritize selected linkages for future research. The starting point for the analyses will be the South Delta Salmonid Research Collaborative (SDSRC) conceptual model that depicts a broad overview of drivers and outcomes, a subset of which are within the CAMT SST scope. The conceptual model will be expanded into one or more specific sub-models to more explicitly depict cause and effect linkages linked to export operations at a finer scale of resolution for use as part of the framework for conducting the analyses. One example is the effect of water exports on water velocity and flows in the south Delta channels and subsequent effects on juvenile salmonids, including migration route, residence time and predation risk. Conclusions of the Gap Analysis regarding the scientific rationale, effect size and effect variability of conceptual model linkages will be based on the best available information. Specifically, we will review existing analyses (published and unpublished) and document how each provides evidence related to how, when and where stressors linked to export operations (identified in conceptual model linkages) can affect different species, life stages, and populations of juvenile salmonids during their migration through the south Delta. The review and synthesis of available information on water project-linked effects on salmonid survival, referred to as a Gap Analysis, is identified as Work Plan Element 1 in the CAMT Salmon Scoping Team Work Plan.

In other contexts, a gap analysis is a planning tool used to assess existing information and identify where future research and analysis should be focused. Here a "gap" is defined as a hypothesized or putative linkage between a specific driver and an outcome where the existence or strength of the linkage requires further evaluation. As such, the SST will conduct a gap analysis on water project-linked effects on factors affecting survival of juvenile salmonids in the South Delta. The objectives of this process are two-fold:

1. Identify linkages characterized by a clearly defined and supported mechanism consistent with best available physical and biological information, as well linkages that represent "gaps" in our current understanding, either because of poorly defined mechanisms, conflicti

The 'requirement for evaluation needs to be supported by criteria or at least questions - in some cases evaluation may not result in 'filling the gap'

'clearly defined and supported' are vague terms

There needs to be some consideration of what is 'knowable' either in terms of the availability of factual information or whether time/ resources are realistically available to 'fill the gap'

mechanisms, and/or data which provides equivocal evidence for importance or certainty; and

2. Prioritize a subset of linkages for further investigation.

element 3 seems to be about tagging studies only - seems unlikely that this will be the only thing that is 'set up'. Suggest removing this as it seems like you know the answer already and limits the objectivity of the process.

tified information gaps will be used to prioritize research questions that can be d via new analyses and/or new investigations. Although this latter step is not identified in the CAMT SST Work Plan Element 1, it is the logical extension of the lysis and sets up CAMT SST Work Plan Element 3. This document briefly outlines ach for the Gap Analysis. Appendix A to this document is an example of the on this approach to three test DLOs that were used as a proof of concept. The Gap will be conducted collaboratively by the SST, which is composed of technical staff National Marine Fisheries Service, the US Fish and Wildlife Service, Bureau of tion, California Department of Water Resources, Delta Science Program, federal water contractors, and academic institutions. As the Gap Analysis proceeds the cipates that refinements will occur to the initial conceptual model and the l process.

## Process Overview

The SST intends to initially use an approach modeled after the Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) using conceptual models as a framework for identifying and evaluating driver-linkage-outcomes (DiGennaro *et al*., 2012), with possible modifications based on other published "weight of evidence" approaches (e.g., Burkhardt-Holm and Scheurer, 2007, Suter II and Cormier, 2011), to identify attributes of each of the linkages. Best available data and scientific literature will be compiled to evaluate these linkages. Based on the compiled evidence, attributes of each linkage will be defined according to:

- Direction of the effect—positive, negative, or threshold response,
- Understanding that underlies the effect (i.e. clarity of mechanism),
- Relative magnitude of the effect, and
- Independence of the effect.

Understanding represents much more than clarity

The Gap Analysis consists of the following sequential steps:

(1) An initial identification of ecological pathways and linkages in the SDSRC Conceptual Model (Figure 1) based primarily on relevance to the SST scope. This will be accomplished via review and discussion of potential linkages and pathways within the SST and refinement and revision of the conceptual model(s). This step is to ensure relevance to the CAMT mission. Based on this initial prioritization, linkages not relevant to the SST's scope will be removed from further evaluation steps at this time.

(2) The relevant ecological linkages will be subject to detailed ev available scientific information including data, published reports, un

Unclear how system-level effects or other aspects of life history are considered relative to these 'linkages' if others are not also considered. Be careful not to limit thinking too early in the process. OR have a larger CM for salmon that this fits into

Submodels within a model becomes too complex and is difficult to follow in the examples. Suggest parsing out individual cause-effect relationships and then grouping

Selection process is not clear

science panel reports, and presentations. Where necessary, sub-models of the conceptual model will be developed to expand and elucidate the more complex linkages. Ultimately, selected linkages will be described, all relevant information will be synthesized and finally, linkages will be categorized and ranked based upon the considerations described in the Approach section below.

Understanding does not equal predictability. That concept seems to have been lost and is potentially very important.

(3) The SST will develop a collaborative report des
(a) generally well understood with a strong scientific foundation; (b) less understood because of conflicting or inconclusive evidence; or (c) largely unknown because of the paucity of information. Most importantly, the report will summarize the scientific support for each linkage using consistent criteria and terminology. It is expected that linka strong scientific support regarding a large effect on survival of Central Valley salmonids in the Delta will support either short-term or long-term management actions to predictably alter that effect and therefore will not require additional analysis or inv will evaluate and prioritize for future investigation the ecological linkag understood or studied but are deemed relevant to improved understan project-linked effects on factors affecting salmonid survival. The SST w model will be refined and updated upon completion of these analyses.

Large is too vague

If you really want predicability then it has to be considered as part of the evaluation. See DRERIP.

Suggest model needs to be refined and updated as new information becomes available. From what ever source the information arises.

## Approach

### *Phase 1: Gap Analysis*

1.1 Prioritize linkages in the revised SDSRC conceptual model and more detailed conceptual sub-models for evaluation based on their relevance to the SST scope. The SST scope is as follows:

The next step describes these are 'selected'. Be clearer on the criteria for what will be included and what will not be included

> *The scope of the CAMT Salmonid Scoping Team is to review existing information and develop new information on salmonid survival as affected by factors linked to State Water Project and Central Valley Project-linked operations, including San Joaquin River inflow, delta exports, and south delta hydrodynamics. The primary focus of this work is the Sacramento-San Joaquin Delta south of the San Joaquin River (including Old and Middle River, the State and Federal Export Facilities, and the Head of Old River Barrier). The geographic scope also includes those pathways and export-related facilities that provide access for Sacramento River salmonids into the central and south Delta, such as the Delta Cross Channel (DCC). The water project-linked effects considered within this scope may include entrainment, hydrodynamics, barriers, predator-prey interactions, food supply, aquatic macrophytes, habitat suitability, and water quality as part of the "driver-linkage-outcome" cascade. The results are intended to contribute information relevant to the ESA consultation on the Long Term Operation of the CVP and SWP.*

This term needs definition. See later comments

1.2 Compile and review scientific information relevant to conceptual model linkages selected for evaluation (data, reports, publications, agency studies, dissertations, expert panel reports, presentations, etc.).

(NOTE: For each of the following linkage attributes evaluation steps, the SST working group of scientists will apply the same ranking system to mitigate bias. Narratives will be prepared documenting the evidence supporting the ranking (e.g., high, medium, etc.) of each of the conceptual model linkages included in the evaluation.)

1.3 Evaluate relevant linkages in the conceptual model based on the compiled scientific information for *direction of effect*. The evaluation will consider how location, time or other circumstances may alter the direction of the effect.

This is a different interpretation than DRERIP used. +/- referred the the nature of the relationship between driver and outcome not the nature of the outcome.

a. Positive - The driver elicits a positive outcome.

b. Negative - The driver elicits a negative outcome.

c. Variable effect - The driver elicits a variable outcome.

Does variable mean + or - depending on circumstances or a complex relationship

d. No effect - Evidence indicates that the driver has no effect

e. Insufficient information available to evaluate driver effect.

1.4 Evaluate relevant linkages in the conceptual model based on the scientific information for *understanding of mechanism.* The DRERIP criteria for scientific understanding (Table 3 in DiGennaro *et al*., 2012), summarized with some prelimin modifications below, will be used initially to rank the evidence available for each lin the conceptual model, with modifications as needed:

Table 3 includes predictability. Seems to be totally missing here

e. High - based on peer-reviewed studies from within the system and scientific reasoning supported by most experts within the system,

f. Medium - based on peer-reviewed studies from outside the system and corroborated by non-peer-reviewed studies within the system,

g. Low - based on non-peer-reviewed research within system or elsewhere, and

h. Minimal - scientific evidence lacking

i. Conflicting – conflicting scientific evide

What happened to 'not widely accepted'?

1.5 Evaluate linkages in the conceptual model based on scientific information for *magnitude of the effect* on the outcome. The evaluation will include consideration of how location, time or other factors may alter magnitude both at the proximate scale and ultimate scale regarding through-Delta survival. The general approach outlined in DRERIP for establishing evaluation criteria for ranking importance (Table 2 in DiGennaro *et a* 2012), modified below, will be used initially to rank the potential importance for eac linkage evaluated:

Define survival - on next page it is 'Delta-wide'

a. High - Evidence indicates potential sustained major effect; the outcome addresses a key limiting factor affecting south Delta-wide survival (e.g., contributes substantially not only to the immediate outcome under consideration, but also the broader outcome of south Delta survival rate).

Or 'through-delta'?

Within or through?

b. Medium - Evidence indicates potential sustained minor effect; the outcome addresses a limiting factor affecting immediate outcome under consideration, but outcome of south Delta-wide survival rate is limited to minor effect on large areas (regions) or multiple patches of habitat

Why is habitat not included above? Or why is it here if this is about survival which is a population factor?

c. Low - Evidence indicates potential limited effect, minor way, or limited spatial (local) or temporal

d. Insufficient information to evaluate relative magnitude of linkage.

Define terms and how they are applied

| Score | Proximate | Ultimate |
|---|---|---|
| High | Evidence indicates potential sustained major effect to the immediate outcome under consideration | Evidence indicates potential sustained major effect; the outcome addresses a key limiting factor the broader outcome of south Delta survival rate). |
| Medium | Evidence indicated potential effect addresses a limiting factor affecting immediate outcome under consideration | Evidence indicates potential sustained minor effect on south Delta-wide survival rate limited to large areas (regions) or multiple patches of habitat |
| Low | Evidence indicates potential limited effect, influences the outcome in a minor way, or limited spatial (local) or temporal habitat effects. | |
| Insufficient | Insufficient information to evaluate relative magnitude of linkage. | Insufficient information to evaluate relative magnitude of linkage. |

1.6 Evaluate linkages in the conceptual model based on *independence of interactions* with drivers other than the focal driver:

The effect of the linkage?

a. High - The linkage is largely independent of interaction with other drivers.

b. Low - The linkage is greatly dependent upon interactions with other drivers.

1.7 *Revise* conceptual model as necessary when linkage suggested by evidence is not accounted for in current conceptual model.

1.8 If evidence suggests different linkage outcomes for salmonid species, Chinook salmon life histories, or perhaps even more defined populations (e.g., San Joaquin River fall-run), consider separate rankings based on relevance to that defined population. This may lead to separate versions of the conceptual model.

This is potentially very helpful. In the examples sometimes it is not clear which run is being considered and/or whether effects may be different

***Phase 2: Research Prioritization***

2.1 Initially, evaluated linkages identified as high/medium *magnitude of effect* and medium/low/conflicting *understanding of mechanism* is considered among priority candidates for further research. This approach to prioritizing linkages is likely to evolve as the Gap Analysis proceeds, and additional criteria may be developed. As part of finalizing the evaluation, CAMT will be briefed regarding relevance of the high priority research topics identified through the SST evaluation and their importance in resolving key scientific issues and informing management decisions in the future.

**Products**

The results of the Gap Analysis will be summarized in a collaboratively produced final report to CAMT (see Schedule below). This report will include (a) a summary of linkages evaluated and their scientific support, and (b) the revised version of the conceptual model(s). Together, the refined conceptual model(s) and linkage rankings will highlight linkages with varying levels of support based on scientific evidence, and certainty. If completed, the results of ranked research priorities (Phase 2) will also be included in the final report. However, if workload and schedule preclude completing the research prioritization phase, it will be completed and reported by the SST in an addendum at a later date. The final rankings, categorizations, and conclusions will be reviewed, revised, and agreed upon by the SST with any differences in opinion included. It is expected that the Gap Analysis and associated set of research priorities will be used to guide future research. The final report will be peer reviewed under the guidance of the Delta Science Program, and revised by the SST as appropriate.

**Schedule**

A draft report on CAMT SST Work Plan Element 1, Gap Analysis, will be completed by September 2014, and provided to the Delta Science Program for peer review. A final report will be submitted to CAMT in November 2014.

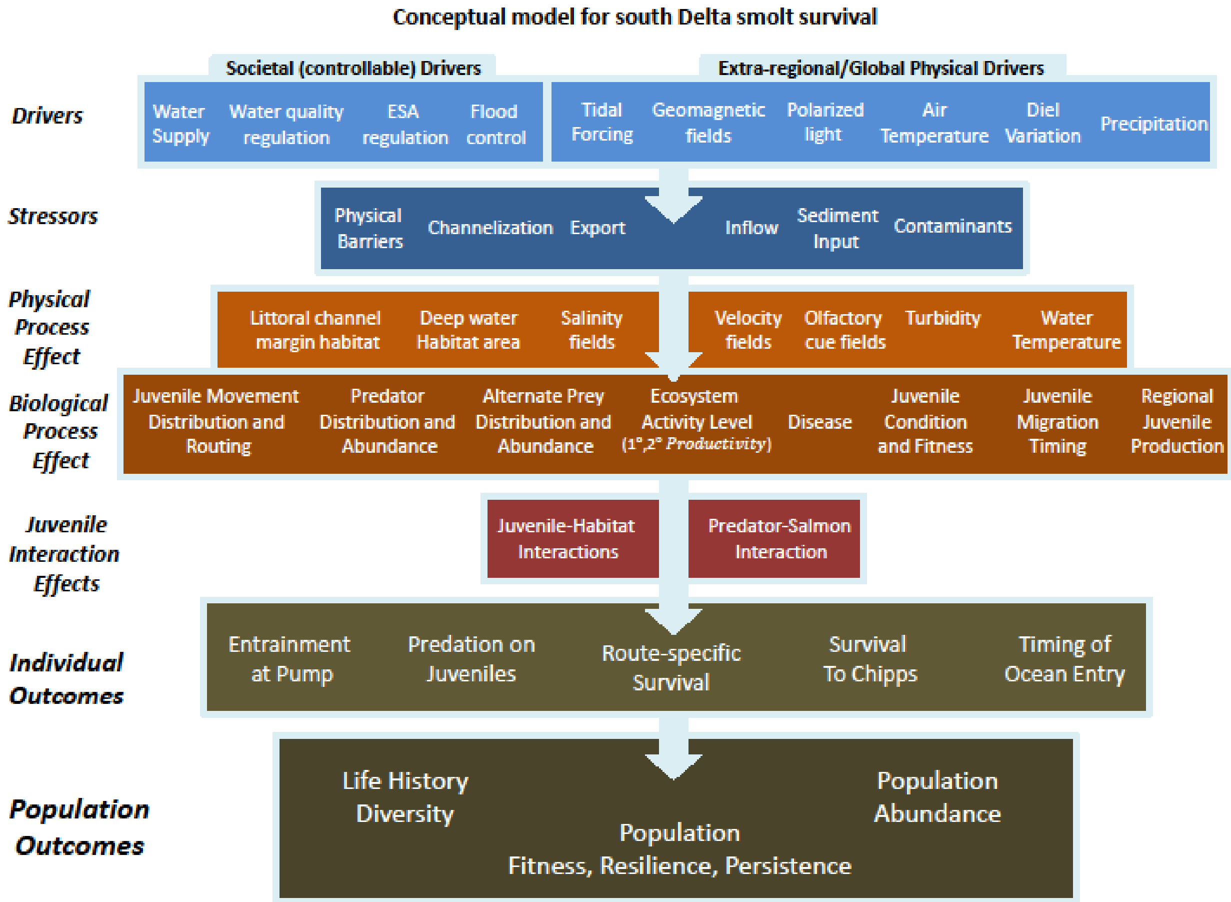



**Figure 1.** **Conceptual Model from the South Delta Salmonid Research Collaborative report to CAMT, February 2014, describing factors affecting survival of juvenile salmonids in the south Delta.**

This diagram is not very helpful. It would be more useful if 'linkages' were identified. However it seems to use such a different approach that it is confusing.

**References**

Burkhardt-Holm, P., and K. Scheurer. 2007. Application of the weight-of-evidence approach to assess the decline of brown trout (*Salmon trutta*) in Swiss rivers. Aquatic Science 69:51-70.

DiGennaro, Bruce; Reed, Denise; Swanson, Christina; Hastings, Lauren; Hymanson, Zachary; Healey, Michael; Siegel, Stuart; Cantrell, Scott; and Herbold, Bruce. 2012. Using Conceptual Models in Ecosystem Restoration Decision Making: An Example from the Sacramento-San Joaquin River Delta, California. *San Francisco Estuary and Watershed Science*, 10(3). jmie_sfews_11181. Retrieved from: http://escholarship.org/uc/item/3j95x7vt

Suter II, G. W., and S. M. Cormier. 2011. Why and how to combine evidence in environmental assessments: weighing evidence and building cases. Science of the Total Environment 409:1406-1417.

# Appendix A: Gap Analysis Approach Proof of Concept

## Appendix A: Gap Analysis Approach Proof of Concept

Upon completion of the “Identification and Prioritization of Gaps in the Current Understanding of Water Project-Linked Effects on Juvenile Salmonid Survival in the South Delta” approach, a subteam was tasked with attempting to use the described method to evaluate Driver-Linkage-Outcome pathways (hereafter referred to as DLOs). For this purpose, three DLOs were selected from an initial list developed by the SST regarding export facility operations and entrainment of Chinook salmon. A preliminary proof of concept exercise was undertaken by subteam members during the week of June 30 and presented to the SST on July 7. This appendix is a final iteration of this preliminary exercise, subject to further analysis and refinement of the analysis process and outcomes of the gap analysis, and contains information presented to the SST and revisions based on their input. While the DLO pathways completed in this document are reasonably representative of what is anticipated to result from the gap analysis, there are numerous other DLO pathways regarding export facility operations and entrainment of Chinook salmon which the subteam did not address. This appendix is provided for illustrative purposes only.

Our first step was to review the South Delta Salmonid Research Collaborative conceptual model and identify what processes and measures may constitute drivers, linkages, and outcomes for a sub-model on this topic (Table 1).

**Table 1. Possible Drivers, Linkages, and Outcomes for a Gap analysis submodel of export facility operations and entrainment of Chinook salmon.**

This use of terminology is so different from DRERIP that a glossary would be essential.

Can drivers be linked to multiple linkages and linkages to multiple outcomes? The use of these lists is not clear.

| | |
|---|---|
| **Driver** | • Tides<br>• Combined operations (e.g., Radial Gate, Louver Cleaning)<br>• Day/Night<br>• Exports<br>• Temperatures<br>• Juvenile proximity (distribution/abundance) |
| **Linkage** | • Efficiency<br>• Predator distribution and abundance<br>• Vegetation/Debris<br>• Facility entrance<br>• Fish behavior<br>• Alternate prey distribution and abundance |
| **Outcome** | • Direct mortality (includes prescreen and entrainment loss)<br>• Salvage<br>• Collection, handling, transport, and release (CHTR) mortality |

Are these considered to be equal in their influence on 'survival' - the overall outcome?

The next step was clarifying the previous hypotheses described by SST members into pathways (Table 2). It was estimated that these well documented DLOs could be reasonably examined within a limited timeframe (~8 hours per pathway) and were thus tractable for the proof-of-concept. Submodels of the conceptual model were developed to elucidate the linkages in each DLO pathway (Figures 1-3).

Source unclear

**Table 2. Original statement regarding export facility operation and entrainment of Chinook salmon and modified Driver-Linkage-Outcome pathway.**

| Original | Modified |
|---|---|
| Volume of exports influences the CVP salvage efficiency. The greater the volume, the higher the facility velocities and the higher the survival to Chipps Island through the facility. | Export velocity affects louver which affects salvage. |
| Predation mortality is higher adjacent to the SWP and CVP (i.e., Grant Line Canal and Old River) than in other freshwater reaches of the South Delta and San Joaquin River salmonid migration corridors. | Juvenile proximity (distribution/abundance) affe distribution and abundance w salvage. |
| Salmon entrainment into Clifton Court Forebay is not affected by diel cycles. | Diel cycles affect fish behavior entrance into facility. |

The assumptions made during the modification should be clear. Does the modified one represent the entire concept on the left side or just a subset? For example, proximity is a continuous concept but the original was a specific places.

The other 2 result in change in salvage - should they all end in salvage to be considered submodels?

**Figure 1. DLO submodel for export e cy - affects salvage.**

Not clear what the double ended arrows represent. Driver should be more specific - velocities where? Be as specific as possible everywhere.

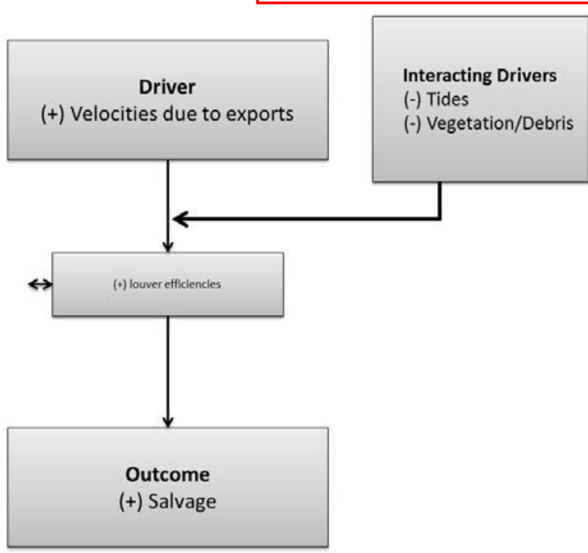


**Figure 2. DLO submodel for juvenile proximity (distribution/abundance) - affects predator distribution and abundance - affects salvage.**

This may be clearer if it was separated into two sections - one dealing with prey dynamics and the other dealing with predator dynamics.

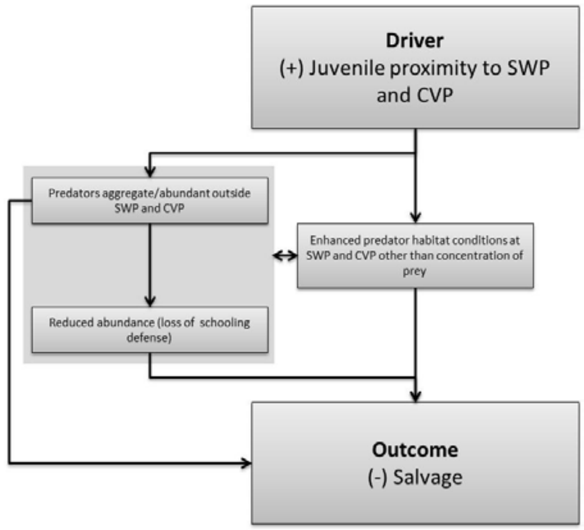
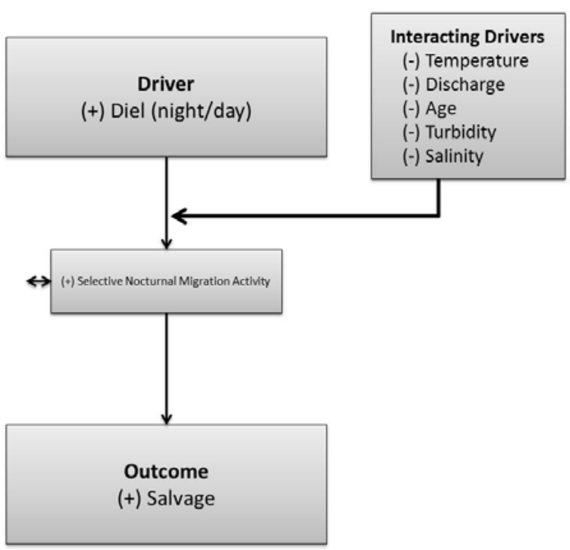



**Figure 3. DLO submodel for diel cycle affects - fish behavior - affects entrance into facility.**

Diagram is not very helpful as too much is implicit.



Using literature sources and other information available to the subteam, standardized narrative forms were completed to document the best available scientific information including data, published reports, unpublished reports, science panel reports, and presentations (Tables 3-5). Upon completion of the tables, the criteria values were placed into a matrix (Table 6). This matrix demonstrates that the criteria used are objective enough to score independent DLO pathways that influence the same outcome differently. These differences will be useful for assessing DLO pathways that require additional analysis and experimentation to evaluate their utility in managing salmonid surviva through the south Delta. Further work to develop narratives for additional DLO pat is necessary to develop a complete score matrix for this topic to consider in identify specific DLO pathways for data assessment synthesis and adaptive management.

Not sure the summary matrix shows that. Critical cross evaluation of the tables would show that. How would the matrix be used in identifying which to move forward with?

Many statements in the tables are vague or need supporting information/citations. Highlights below indicate these.

**Table 3. Narrative table for export efficiency affects louver efficiency affects Chinook salvage.**

| | |
|---|---|
| **Direction** | **Variable Outcome:**<br><br>Numerous lab and field studies have evaluated velocities influence on louver efficiency and noted that efficiencies at the same velocities have decreased through time (Bates and Vinsonhaler, 1961; Haefner and Bowen, 2002; Bowen *et al*., 2004). While the current equation (CDFW, 1986) used to describe the relationship between velocities and louver efficiency is positive, many studies demonstrate more variable empirical estimates of efficiency possibly due to other drivers influencing the mechanism (Bates and Logan, 1960; Bates and Vinsonhaler, 1961; Karp *et al*., 1995; Bowen *et al*., 1998; Haefner and Bowen, 2002; Bowen *et al*., 2004). |
| **Understanding of mechanism** | **High Understanding:**<br><br>The ambiguity in the quotations below doesn't seem to support high rating<br><br>Migratory juvenile Chinook behavior, louver efficie velocity is well understood. These principles under construction, and operations of the fish collection f likely some interaction between louver efficiency a Many publications have recognized that the louver relationship is complex and not linear. Karp *et al*. (1995) stated; “The relationship between louver efficiency, flows, velocities, tides, and debris loads is complex and we cannot clearly state which factor more strongly influences performance of the primary system. However, efficiencies were lowest when conducted during low flow/low velocity conditions, and when the louver screens were clogged or out of the water for cleaning. “ Bowen *et al*. (2002) stated “conflicting results leave us without a consistent relationship between approach velocity and Chinook salmon secondary louver efficiency.” |
| **Proximate magnitude of the effect on the outcome** | **Medium Magnitude:**<br><br>The potential effect of louver efficiencies in salvage addresses a limiting factor in the fish protection facilities. It affects the immediate outcome under consideration (salvage). |
| **Ultimate magnitude of the effect on the outcome** | **Medium Magnitude:**<br><br>Only a small fraction of the salmonid populations in the Central Valley enter the facility and are exposed to the louvers. Due to the local scale of the effect of velocity and the interaction of other drivers in the outcome, evidence indicates the potential effect on the outcome is sustained (exports are pretty continuous) but minor spatially. |
| **Independence of interactions with other drivers** | **High**, but other drivers interact.<br><br>**Tides**: Tides are a very influential modulator of this independence given that they happen half the time. Tidal effects are more influential when exports are lower.<br><br>Tides don't 'happen' - do you mean specific tidal flows?<br><br>**Louver cleaning**: Only likely an issue wh plants or pulled up for cleaning. This occurs approx. 60% of the time up to 480 min., but averaging less than 120 min. per day (CFS 2013). |

**Table 4. Narrative table for juvenile proximity (distribution/abundance) affects - predator distribution and abundance - affects salvage DLO pathway.**

| | |
|---|---|
| **Direction** | **Negative:**<br><br>Increase in proximity (i.e., spatially closer) to SWP or CVP increases predation risk mortality (decrease salvage). |
| **Understanding of Mechanism** | **General evidence of lower survival for migrations routes near export stations:**<br><br>For Sacramento origin fish, route-specific survival is lower thr What about SJ fish? the interior Delta (south Delta) where export facilities are loca compared to routes through Sacramento River and Sutter and Steamboat Sloughs (Perry, 2010).<br><br>**General evidence supporting the existence of a dynamic predation environment that could set up a "hot spot" near the CVP or SWP facilities:**<br><br>-At CCFB, a meaningful number of predator-sized striped bass flux through the radial gates on very short timescales (Gingras and McGee, 1997).<br><br>-Shallow water piscivores are widespread in the Delta and generally respond in a density-dependent manner to seasonal changes in prey availability (Nobriga and Feyrer, 2007).<br><br>-Predators can consume large numbers of juvenile salmon in a short period of time (e.g., Shively *et al*., 1996)<br><br>**Mechanism 1 Aggregated predators at SWP and CVP (High Understanding):**<br><br>Predators aggregate in areas where flow modulation and prey are present: at CCFB/SWP (Clark *et al*. 2009). Striped bass congregate near screens and louvers (Brown *et al*., 1996); WIDD (Sabal, 2014); out of basin (Rieman *et al*., 1991; Ward *et al*., 1995). More predators = more predation.<br><br>**Mechanism 1.a Reduction in patch size (Minimal Understanding):**<br><br>Increased duration of migration period, mortality among cohorts, and overall low abundance leads to disruption of defensive mechanisms such as ability to school contributing to increases in vulnerability to predators at potential hotspots (e.g., CCFB; Petersen and DeAngelis, 2000). Interacts with aggregation of predators. |

| | |
|---|---|
| | **Mechanism 2. Enhanced Local Predation Conditions:** No rating?<br><br>The SWP and CVP export facilities increase habitat modifications that enhance sensory capabilities of predators (i.e., reduced turbidity increases risk of predation (Gregory and Levings, 1998), velocity and turbulence associated with CCFB radial gate operation (Clark *et al*. 2009), and habitat for predators (SAV, FAV)). |
| **Proximate Magnitude** | **Mechanism 1 Aggregated predators at SWP and CVP:**<br><br>Predators abundant in the vicinity of export facilities (Brown *et al*., 1996)- support significant predation potential (Rieman *et al*., 1991; Ward *et al*., 1995). The current Sacramento River striped bass population of roughly $1{\times}10^6$ adults is estimated to consume about 9% of winter-run Chinook salmon outmigrants (Lindley and Mohr, 2003).<br><br>**High**-San Joaquin River: close to 50% of all SJR fish pass export facilities.<br><br>**Medium**-Sacramento River: route specific passage limits exposure to predation for Sacramento origin fish at SWP and CVP facilities. For a December release group, 64.8% of fish took migration routes largely consisting of the Sacramento River and 35.2% migrated into the interior Delta via the Delta Cross Channel and Georgiana Slough. In contrast, only 8.8% percent of fish migrated into the interior Delta through Georgiana Slough in January when the Delta Cross Channel was closed, with the remaining 91.2% migrating mostly within the Sacramento River (Perry, 2010)<br><br>**Mechanism 1.a Reduction in patch size:**<br><br>**Insufficient** No local examples. Available information is limited to application of a theoretical model (Petersen and DeAngelis, 2000).<br><br>**Mechanism 2. Enhanced local predation conditions:**<br><br>**Medium** Evidence of high rates of tag loss in channels approaching export facilities (VAMP 2011). Many of the SJR fish were observed in the vicinity of export facilities.<br><br>In the Sacramento River the current striped bass population of roughly $1{\times}10^6$ adults is estimated to consume about 9% of winter-run Chinook salmon outmigrants (Lindley and Mohr, 2003).<br>At Woodbridge Irrigation District dam (WIDD), 10-29% of the juvenile salmon population migrating downstream in the Mokelumne River was estimated to be consumed by striped bass (Sabal, 2014) |

| | |
|---|---|
| **Ultimate Magnitude** | **Mechanism 1 Aggregated predators at SWP and CVP:**<br><br>**Insufficient.** Stock/race- specific exposure remains unclear to make expansion to Delta scale.<br><br>**Mechanism 1.a Reduction in patch size:**<br><br>**Insufficient** to make Delta scale assessment. Limited to theoretical predation loss estimates.<br><br>**Mechanism 2. Enhanced Local Predation conditions:**<br><br>**Insufficient** to make Delta scale assessment. Indirect support for proximate relationship. |
| **Independence of Interactions with Other Drivers** | For all Mechanisms:<br><br>**Low**<br><br>Minimal independence<br><br>Interacts with:<br>Tides<br>Combined Operations (Radial Gate, Louver Cleaning)<br>Day/Night<br>Exports<br>Temperatures |

**Table 5. Narrative table for diel cycle affects - fish behavior affects - entrance into export facility.**

| | |
|---|---|
| **Direction** | **Positive Outcome (night positively affects entrainment risk):**<br><br>Acoustic telemetry data for age-1+ late fall-run Chinook salmon showed predominantly nocturnal migration in the upper Sacramento River, which diminished with distance downstream (Chapman *et al*., 2012). While no distinct diel pattern was detected by the time the fish reached San Pablo/San Francisco Bay, a statistically significant tendency toward nocturnal migration was still discernible in the tidal Delta (69% of juvenile detections were at night). Unpublished salvage data (1993-2010), which is an indicator of entrainment, also demonstrates greater salvage density (expanded salvage/thousand acre feet) during night hours. Studies of sea run Atlantic salmon have also found that more juveniles migrate at night than during the day (Ibbotson *et al*., 2006 and other studies cited therein). |
| **Understanding of Mechanism** | **High Understanding:**<br><br>Although the underlying physical mechanisms controlling nocturnal migration are not well understood, the positive influence of night on the tendency of juvenile Chinook salmon, and related salmonid species in other systems, to actively migrate in the Sacramento River is well understood. |
| **Proximate Magnitude of the Effect on the Outcome** | **Medium Magnitude:**<br><br>Chapman *et al*. (2012) and Ibbotson *et al*. (2006) both indicate that diel migration activity is affected by a number of other drivers, and salvage data indicates a sizable portion of Chinook salmon are still participating in salvage during the day; therefore the proximate effect is medium. |
| **Ultimate Magnitude of the Effect on the Outcome** | **Low Magnitude:**<br><br>In Table 3 almost exactly the same text results in a medium rating. Might need additional explanation so it doesn't appear inconsistent.<br><br>While evidence indicates the eff small fraction of the population is exposed to the export facilitie with the large influence of other suggest the ultimate magnitude of the diel cycle on salvage is low. |
| **Independence of Interactions with Other Drivers** | **Minimal Independence**:<br><br>Nighttime-specific migration activity diminishes at higher water temperatures (Chapman *et al*. 2012, Ibbotson *et al*. 2006), and is muted by the influence of river discharge, turbidity and possibly age and progression through the migration season (Chapman *et al*. 2012). |

**Table 6. Combined scores for DLO pathways evaluated in preliminary proof of concept.**

| Driver | Linkage | Outcome | Direction | Understanding | Proximate Magnitude | Ultimate Magnitude | Independence |
|---|---|---|---|---|---|---|---|
| Export Velocity | Louver Efficiency | Salvage | Variable | High | Medium | Medium | High |
| Proximity | Predator Abundance | Salvage | Negative | High | High (SJR)<br>Medium (SAC) | Insufficient | Minimal |
| Proximity | Reduction in Prey Abundance/ Schooling Defense | Salvage | Negative | Minimal | Insufficient | Insufficient | Minimal |
| Proximity | Predation Opportunity due to Favorable Habitat Conditions | Salvage | Negative | Medium | Medium | Insufficient | Minimal |
| Diel Cycle | Fish Behavior | Participation | Positive | High | Medium | Low | Minimal |

Reviewer Name: *removed* - Review of Identification and Prioritization of Gaps in the Current Understanding of the Water Project-Linked Effects on Juvenile Salmonid Survival in the South Delta Proposal

I am not familiar with the South Delta issues related to water so this makes it difficult to review this proposal fully. That being said, I have done my best to provide a review of the proposed process of identifying and prioritizing gaps in the current understanding of the effects of water projects on juvenile Chinook salmon.

The title of the proposal does not reflect the stated objectives on the bottom of p. 1. In addition to identifying gaps, the objective is "identify linkages by a clearly defined and support mechanism consistent with best available physical and biological information,….". I read the proposal to include the this and believe it should be in the title. If that is not the purpose, this should be in the title and the objective re-written.

An aim of the proposal is to identify key gaps in the understanding of the effects of water projects on juvenile Chinook salmon. This is premised on the model that was shown in Fig. 1. I wondered if this model has been evaluated in the same manner – are there key factors that are not being considered? I think that this is a critical step. If it has been done, then that should be stated. If not, I think it should be part of the assessment because the success of any work done using the model will depend on the quality and completeness of the model.

The conceptual model shown in Fig. 1 is for "water project-linked effects". Does this mean that there are other sources of effects? If so, I question the validity of an approach that considers project effects in isolation. It is imperative to discuss why water projects are considered in isolation and the potential implications to the success of actions taken as a result of using water project only model. At the very, least the potential effects of other factors and the interaction with water project effects should be included and discussed. I appreciate that this is difficult and will make things more complicated than they are already. However, the failure to do will likely produce questionable and incomplete understandings.

The approach of this effort seems to be that there is a uniform and single response by the population to the identified factors. This is not stated explicitly but is my interpretation from reading the proposal. There is a growing recognition in the scientific literature about importance of diversity within populations in regard to life-histories. This could be a critical determinant of how a population is affected by a given action or actions. Decreased diversity in the affected population could be a major gap to consider but it doesn't appear to be identified in the model.

Another gap that is not clear if it would be considered in the proposal is the shape of the population response curve to the various stressors. The shapes will likely vary depending on the stressor and having the correct shape will be critical to the application of results and the success of any actions. I suggest that you consider building the conceptual model using either a Bayesian (see Marcot et al. 2006. Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. Canadian Journal of Forest Research 36, 3063–3074. ) or Ecosystem Management Decision Support (Reynolds et al. 2014. Making Transparent Environmental Management Decisions. Springer Berlin Heidelberg; Wainwright et al. 2014. Measuring Biological Sustainability via a Decision Support System: Experiences with Oregon Coast Coho Salmon. in: Reynolds et al., editors Making Transparent Environmental Management Decisions. Springer Berlin Heidelberg. P. 277-298.) approach as part of this project.

# Identification and Prioritization of Gaps in the Current Understanding of Water Project-Linked Effects on Juvenile Salmonid Survival in the South Delta

## (Salmonid Scoping Team Work Plan Element 1)

Independent Scientific Review Comments

1. Is the outlined approach sound and reasonable to ensure objective, transparent and comprehensive review of the state of the science regarding water project-linked effects on juvenile salmonid survival in the South Delta?

- Firstly, I would suggest the scope of the review as stated in this first question is potentially too narrow to be informative. The state of science that is drawn upon should be more than just the experiences and data from salmon related to water projects in the south Delta. As has been drawn on for the DRERIP conceptual model on Chinook salmon (Williams 2010), critical information on the genetics, ecology, and population dynamics of juvenile salmon that is important to the south Delta needs to be synthesized from the broader literature on the watershed-ocean transition of juvenile salmonids (primarily *O. tshawytscha*). Certainly, there are some unique conditions and responses of Central Valley salmonids to the Delta and the water operations, but data and experiments from this region are somewhat limited in scope, applicability and current scientific technology. It will not help this deliberation to assume that salmon in the Delta are so unique that no other information would contribute to understanding the effects of water project-linked effects.
- Although the draft conceptual model for south Delta smolt survival will likely require modification (see #2, below), the process to evaluate individual and cumulative DLOs is reasonable and useful, nonetheless. One of the more important elements of the DRERIP conceptual models (DiGennaro *et al.* 2012) is the explicit inclusion of the fundamental assumptions and concepts that underlie the linkages and pathways. This needs to be incorporated into the CAMT conceptual model such that the 'best science' foundation is evident and, perhaps more important, any deviations of that found or expected of juvenile salmon in the south Delta is rationalized on a scientific basis.
- I am unsure whether this is a question of the structure of the CAMT conceptual model or of the CAMT process itself? Like all conceptual models, the structure emerges as somewhat of the "best explanation", although often that is constrained somewhat by the participants who assembled or reviewed the model. There are two issues that can't necessarily be incorporated into the CAMT conceptual model but could be in the process?
    - Some way to consider alternative explanations/mechanisms for critical linkages, pathways, (physical or biological processes and interactions

needs to be accommodated. For instance, there are divergent results and opinions about the predictability or consistency of many juvenile salmon behaviors that underlie the assumptions about their responses to temperature, velocity, salinity, prey, etc. fields that often result in somewhat "hidden" uncertainty. How are resulting divergent linkages and pathways given due consideration, or at least evaluated?

  - How is or might randomness or stochasticity incorporated? Optimally, random or stochastic linkages, pathways and processes would somehow be featured in the CAMT conceptual model. Alternatively, it should be an explicit component in the (1.3.c) Variable Effect option of Direction of Effect, or an entirely different direction because a variable effect could still be deterministic (non-linear). At the moment, the model appears to be very deterministic. Yet, there are random/stochastic elements in many of the conceptual model steps, which propagate through various effects into individual and population outcomes. At the minimum, the associated uncertainty should perhaps be identified such that the sensitivity of the associated linkages and pathways would be associated with unmanageable effects?

- The latter point might offer the question of whether the conceptual model offers the means for a sensitivity analysis for alternative linkages/pathways. Or, would this be considered the same as assessing the magnitude of effect?
- The Direction of Effect may deserve further enhancement to accommodate more complex responses? For instance, some physical and biological process could demonstrate threshold responses or hysteresis? Not only do some physical processes demonstrate hysteresis but time lags due to prior inputs, variable storage and multiple interacting drivers are also common in ecological systems (Bestelmeyer *et al.* 2011). Two examples of hysteresis/threshold phenomena in the CAMT conceptual model might be juvenile salmon prey and habitat switching.
- One nagging question that I have is whether the CAMT conceptual model is intended to capture the cumulative, propagative effect of Chinook salmon life history diversity on long-term population resilience. Survival of juvenile Chinook salmon through the south Delta is not the only determinant of population resilience (see Ecology and Society special feature on Pathways to Resilient Salmon Ecosystems, 2009 or Bottom *et al.* 2011 for synopsis of influence on salmon resilience). Survival of divergent life history types through the Delta, rather than the dominant or supposedly "optimum" life history type, is more likely to be the objective to promote long-term population resilience of Central Valley Chinook salmon.

### 2. Is the process likely to succeed in documenting scientifically well supported linkages, describing key scientific uncertainties and identifying research gaps? Will it support collaborative science?

- Much may depend upon scientific input and peer review of the fundamental conceptual model. My initial view of the model prompted some perplexity about the model structure or components (including lack thereof), even though I am relatively familiar with the DRERIP conceptual model formulation. For instance:

- Life history diversity appears principally as one of the Population Outcomes but should also be included as a population structure that at the <u>initiation</u> of the process; in theory, it could be one of several population structure factors under *Drivers*
- Juvenile life history interactions, including hatchery-wild, should be a factor in *Juvenile Interaction Effects*
- Residence time should be a factor in *Individual Outcomes*

- To a considerable degree, driver-linkage-outcomes developed in conceptual models are just that—conceptual. At least for what is proposed to be the dominant drivers and linkages to important/sensitive outcomes, numerical modeling should be employed to validate them. Development of such quantitative (both statistical and dynamic numerical) models may be most feasible for sub-models that are based on detailed empirical datasets.
- Collaborative science can be accommodated, and even promoted, by CAMT process but it will depend to a large degree on access and transparency—access for diverse views and perspectives, and transparency of the assumptions and sources of both concepts and data.
- While research priorities might be delayed (appearing in an addendum) the sensitivity of variables with high degree of uncertainty need to be in final report to CAMT.

3. What are the key areas of research team's technical expertise that would be essential for the successful completion of the proposed work?

- In my opinion, a critical addition, if not already represented, is a regionally-specific climate scientist. There needs to be incorporation of both the current climate variability and future climate change effects.
- While I'm sure there are ample numerical modelers of physical processes (e.g., hydrology, tidal circulation, suspended sediment and other particle transport, etc.) involved in evaluating and prioritizing gaps in our current understanding, it would be important to have a systems modeling capacity in order to link these processes with both the south Delta landscape and migrating salmon population parameters. Someone with a background in salmon life cycle models (e.g., such as *Shiraz*; Scheurell *et al.* 2006) , especially expert in complex salmon life history patterns such as that of Chinook, would be particularly desirable.
- Perhaps an agent-based model practitioner, especially someone who is adept at visualization tools?

4. Are there some novel ways the research team should consider for presenting the results?

- A scenario approach might be one of the more understandable and acceptable ways to illustrate the potential multiple and alternative pathways through the conceptual model, to illustrate both water project-associated management options but also variable and stochastic behaviors even under the same management actions.

- Dynamic visualization of the CAMT conceptual model could also be a worthwhile, albeit investment heavy, means to present the results. This might offer the means to illustrate not only the effect of different directions and magnitude of effects, understanding of mechanism and independence of interactions in predicting individual and population outcomes, but also the inherent uncertainty/variability in the physical, biological and juvenile interaction effects. Random/stochastic effect could be incorporated using Mote Carlo methods?

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**Review of**

# Identification and Prioritization of Gaps in the Current Understanding of Water Project-Linked Effects on Juvenile Salmonid Survival in the South Delta (Gap Analysis Proposal)

Reviewer Name *removed*

**For the Delta Science Program**
**9/ /2014**

The Delta Science Program has asked the reviewers to "read, review, and comment on Gap Analysis Proposal and background material provided," to answer several review questions, and to give advice on improving the proposed approach. The questions are:

1. Is the outlined approach sound and reasonable to ensure objective, transparent and comprehensive review of the state of the science regarding water project-linked effects on juvenile salmonid survival in the South Delta?

2. Is the process likely to succeed in documenting scientifically well supported linkages, describing key scientific uncertainties and identifying research gaps? Will it support collaborative science?

3. What are the key areas of research team's technical expertise that would be essential for the successful completion of the proposed work?

4. Are there some novel ways the research team should consider for presenting the results?

Of the background material, the most important is the "Progress Report to the Collaborative Science Policy Group" (Progress Report), written by the Collaborative Adaptive Management Team (CAMT). At page 11, this notes that "The Delta Science Program will oversee independent review of workplans …" and "Provide guidance on scientific methods and best practices to be used in developing and implementing workplans …" I assume that this review is part of this process. As such, this is not a review of the relevant science as much as it is a review of management of the relevant science. That is, as the full title of the Gap Analysis Proposal indicates, this is about process rather than substance. I do not know that I am an expert on the management of science, but I was deeply involved with a somewhat similar litigation-related program of study, and have watched attempts to manage studies of Central Valley Chinook and the Delta for many years, so I will do my best to provide helpful suggestions. First, I offer some general comments, and then try to answer the questions and discuss some specifics.

**Introductory Comments:**

As described at p. 58 in the Progress Report, the 209 Biological Opinion on long-term operations of the SCP and SWP (BiOp) includes two "reasonable and prudent actions" that are intended to increase the survival of juvenile Chinook and steelhead migrating through the Delta. These RPAs regulate reverse flows on the Old and Middle rivers, and the ratio of San Joaquin River inflows to Delta exports (I:E ratio). Reverse flows and the I:E ratio are hoary topics that have been argued since well before I became involved with Central Valley salmon issues about 25 years ago, evidently without resolution. According to the Progress Report: "Whether I:E ratio or OMR flows are appropriate metrics for linking to salmonid survival is subject to different views. Some feel that both metrics are useful, and some question the use of either metric as a factor influencing salmonid survival."

Through some procedural steps that I do not completely understand, recent litigation over the BiOp for Chinook and steelhead, and a separate BiOp for delta smelt, resulted in the creation of the Collaborative Science and Adaptive Management Program (CSAMP), comprised of a Collaborative Science Policy Group (Policy Group), which oversees the Collaborative Adaptive

Management Team (CAMT). Finally, the Gap Analysis Proposal was written by a sub-group of the CAMT called the Salmonid Scoping Team (SST).[1]

To step back a bit, the CVP and SWP both operate large dams on the Sacramento River and its tributaries. Water released from these dams flows down the rivers to the Delta, and then across the Delta to two large pumping stations. “Exports” from these pumping stations supply water to agricultural and municipal uses south from the Delta. Water from the San Joaquin River is also drawn across the Delta to the pumps. At the same time, populations of Chinook salmon and steelhead reproduce in both rivers and in hatcheries, and naturally produced juveniles and some hatchery juveniles have to migrate through the Delta to reach the ocean. People value both the exports and the fish, and there has been controversy about the effects of the exports on the fish since before the pumping stations were built, over 60 years ago in the case of the CVP. Both delta smelt and juvenile salmonids are entrained by exports, and the RPAs mentioned above are intended to limit that entrainment. The controversy has motivated many studies and study programs, and the Collaborative Science and Adaptive Management Program, a workplan for which is under review here, is simply the latest step in a long process.

Finally, it seems appropriate to note my own view on this matter, at least for salmon, which is given in Williams (2006:313), I do not have a clear view regarding delta smelt:

> It seems clear that the Delta pumps are a problem for Central Valley Chinook, especially for San Joaquin River Chinook, and presumably the problem will increase as pumping increases. Nevertheless, it does not appear that the pumps *per se* are **the** problem. Probably because of the assumption that juvenile salmon would passively follow the water (e.g., Erkkila et al. 1950), the pumps have received more attention as a factor in the decline of salmon and other fishes than seems justified by the available evidence. That said, it seems artificial to consider the pumps separately from truncated habitat, reduced spring flows, freshening of the Delta, and other changes in Central Valley salmon habitats that result from the entire system for water management, of which the pumps are an important part. The critical point is that Central Valley salmon would benefit from a more rational allocation of management attention over problems.

**General Comments:**

The Court Order described in the Progress Report contemplates a major effort to understand better the effects of the CVP and SWP facilities and their operation on delta smelt, Chinook, and steelhead. Such an effort would require careful management to work with any efficiency, even if it did not involve parties who have long been adversaries, and a tight schedule. Whoever is trying to manage it has my full sympathy, and will need to walk a fine line between stifling the process with too much structure on the one hand, and allowing it to devolve into a set of poorly related studies that mainly reflect the interests or viewpoints of particular parties.

The Gap Analysis Proposal describes a structured process for reviewing what is known about how juvenile Chinook and steelhead in the South Delta are affected by the operation of the CVP and SWP facilities, especially the project pumps. The process is modeled after the Delta Regional Ecosystem Restoration Implementation Plan (DRERIP), “using conceptual models as a

[1] You can’t tell the players without a scorecard.

framework for identifying and evaluating driver-linkage-outcomes, with possible modifications based on other published "weight of evidence approaches" (citations omitted). Figure 1 in the Gap Analysis proposal shows the primary conceptual model to be used, based on one developed by a pre-existing South Delta Salmonid Research Collaborative (SDSRC). The expected results of the process are "a summary of linkages evaluated and their scientific support," and a revised version of the conceptual model or models.

**Concerns:**

I have three main concerns about the Gap Analysis Proposal: 1) that the scope of the inquiry will be too narrow; 2) that the process will be too structured, such that creativity and taking a broad view will be discouraged; and 3) that the SDSRC conceptual model may not be as helpful as it should.

1. *The scope of the inquiry:*

Intelligent people have been studying the effects of the pumps on juvenile Chinook since the "pre-project" work of Erkkila et al. (1950), without resolution. This may result simply from the difficulties of studying small fish in a great expanse of turbid water, but it may also be that people are not asking the right questions. My impression is that the Gap Analysis proposal, as well as the Progress Report with respect to salmon, reflect what Bottom et al. (2005) called "production thinking," as opposed to "population thinking," and this may lead to an overly narrow approach to the issue.[2] To quote from Ch. 1 of Williams (2006):

> Bottom et al. (2005, Ch. 2) argued that the utilitarian foundation of early salmon management resulted in "production thinking," a point of view that "... measured success by the output on natural resources (e.g., pounds or numbers of salmon, angler-days of use, etc.)" and "emphasized short-term changes in the abundance of salmon, which were defined arbitrarily as any geographic unit of management interest (e.g., river basin, state, nation)." As an alternative, Bottom et al. (2005) argued for what they call "population thinking," which they contrast with production thinking in a table, reproduced below. The emphasis is on local populations, diversity in life history patterns, and the varied habitats that support different life history patterns.

To give the context for this quotation and to elaborate the general idea, I have attached the relevant section from Williams (2006) as an appendix.

As an example of how "production thinking" may influence the CAMT studies of salmon, note that in step 1.8 of the Phase 1 Gap Analysis, the default assumption is that juvenile salmonids are alike in terms of the effects of the project upon them: "If evidence suggests different linkage outcomes for salmonid species, Chinook salmon life histories, or perhaps even more defined populations (e.g. San Joaquin River fall-run), consider separate rankings based on relevance to that defined population. This may lead to separate versions of the conceptual model." It seems to me that the default assumption should be that the effects of project operations will be different juvenile life history patterns, as described for example in the DRERIP conceptual model for juvenile Chinook and steelhead (Williams 2010), and on the two different species. Otherwise, I

[2] As I recall, the distinction between production and population thinking had a brief currency among CV salmon biologists after Dan Bottom gave a plenary presentation at an early CALFED Science Conference, but then seemed to fade out of consciousness.

suspect that fingerling migrants to the Delta will be taken as the normative type, at least for Chinook, and that fry migrants will get too little attention, despite recent evidence of their importance (Miller et al. 2010).

As another example, the table referred to in the quotation from Bottom et al. (2005) lists an evolutionary perspective as an attribute of population thinking. To see how this might matter, consider the following hypothetical, which I regard as plausible. The Progress Report notes at p. 58 that "There is general agreement that the survival of emigrating salmonids from the San Joaquin River System through the south Delta has declined in recent years and is now very low." Although I have not checked the most recent data on the origin of fish recovered in the spawner surveys, data from a few years ago indicated that a large fraction of fall Chinook spawners in the San Joaquin tributaries were strays from project hatcheries on Sacramento River tributaries, especially the Feather River Hatchery. There are good reasons to think that the progeny of these fish may have lower fitness in the wild than the progeny of locally adapted natural populations (Christie et al. 2014), and it seems plausible that reduced migratory ability could be a part of such loss of fitness, especially because many hatchery fish have been trucked around the Delta. If this is the case, then the reduced survival through the south delta may reflect a change in the fish rather than, or as well as, changes in the Delta environment. My impression is that this possibility is outside the range of factors likely to be considered in the Gap Analysis.

*2. The structure of the inquiry:*

Although I appreciate the importance of having a framework for processes such as the Gap Analysis, I suspect that the driver-linkage-outcome construct and the DRERIP criteria will hurt more than help. People differ in their habits of mind, and evidently many people support this approach, but personally I find it mind-numbing,[3] and think it filters and distorts information. Table 3 in the Gap Analysis, "Narrative table for export ~~efficiency~~[4] velocity affects louver efficiency affects Chinook salvage," illustrates this point. From the box for "Direction," we learn that the efficiency at the same velocity has decreased over time, and that many studies of the relationship between velocity and efficiency have given variable results, "possibly due to other drivers influencing the mechanism." Nevertheless, in the next box, for "Understanding of mechanism" we find a ranking of high understanding, based on an assessment that "(M)igratory juvenile Chinook behavior, louver efficiencies, and export velocities is (sic) well understood, although the text in the box also includes quotations saying that "The relationship between louver efficiency, flows, velocities, tides, and debris loads is complex and we cannot clearly state which factor more strongly influences performance of the primary system …", and "… conflicting results leave us without a consistent relationship between the approach velocity and the Chinook salmond secondary louver efficiency." Then, in the bottom box we find that the independence of the velocity effect is ranked high. These contradictions seem to me to result from filling in one box at a time, and from being obligated to select one of a few possible rankings.

[3] I found the DRERIP framework restrictive and unhelpful when I wrote the DRERIP conceptual model for juvenile Chinook and steelhead, and abandoned it completely when I revised that report for publication.
[4] Based on Table 2, it appears that there is typo here, which I have corrected.

The CAMT properly noted the importance of being creative and "thinking outside the box" (Progress Report, p. 2). However, I suspect that the process described for the Gap Analysis will tend to contain thinking "within the box." For example, according to the introduction, "(S)pecifically, we will review existing analyses (published and unpublished) and document how each provides evidence related to how, when and where stressors linked to project operations (identified in conceptual model linkages) can affect different species, life stages, and populations of juvenile salmonids during their migration through the South Delta." To the extent that the conceptual model defines a box, this language, and other language in the Gap Analysis Proposal, seems to me to describe a process that will be contained within it.

*3. The Conceptual Models:*

Attention to conceptual models helps when it promotes clear thinking and communication. It is not possible to think usefully about something without having a conceptual model of it, and it is often useful to make the model explicit by writing or sketching it out. This is particularly important for groups, since people working from different conceptual models tend to talk past each other. However, as with numerical models, the real attention should always be on the actual thing that is being modeled, not the model itself. Moreover, in my experience, scientists have different attitudes toward conceptual models; some find careful attention to explicit conceptual models very helpful, some find it mostly a waste of time, and most are somewhere in-between.

I am concerned that the DLO framework, which itself is a kind of conceptual model, and the SDSRC conceptual model, are overemphasized in the Gap Analysis Proposal and in the Progress Report. This may be because I don't understand the SDSRC conceptual model. To me, it looks like a list of things people think are important, arranged in rows starting with "drivers" and ending with "population outcomes." Arrows pointing from one row to the next suggest some hierarchy, but how things in one row influence the things in the next row or following rows is not addressed. Initially, I thought that the ways that things on one row influence things in lower rows are the "linkages," and these would be elucidated by the Gap Analysis. However, in Table 4-7 in the Progress Report, things in the rows are listed under the heading: "Conceptual Model Links." Are these "links" different from the "linkages?" And, the outcomes listed in the bottom two rows depend on many more aspects of the projects than the things listed in the higher rows. For example, timing of ocean entry, listed in the Individual Outcomes row, probably is affected by the timing of emergence from the gravel, which now occurs about a month earlier because releases from the project dams make the water downstream warmer in the winter, and the length of the incubation period depends strongly on water temperature.

In the Progress Report, I understand the study questions listed in Table 4-7, and the titles, but I do not understand what the "conceptual model links" bring to the party. For example, I see how the first three studies listed in the table deal with velocity fields, but it is not clear to me how pointing this out helps. At the least, the conceptual model needs a user's manual.

**Suggestions for improving the proposed approach:**

*Take a broad view of the problem.*
This has been discussed above in terms of production and population thinking. In particular, pay more attention to navigation and other behaviors of juvenile salmonids, and the possible shortcomings of studies using hatchery fish.

*Don't let the DLO framework or other conceptual models be straitjackets.*
Some say that "guns don't kill people; people kill people." Similarly, people, and not the DLO framework or other conceptual models, will write the gap analysis. To the extent that the people involved used the DLO framework and conceptual models simply to give some structure to their work, the process may work well enough, but I am not comforted by the "proof of concept" examples. The participants should take care to let the physical and biological evidence, and not the structure of the process, dominate the gap analysis. At the end of the process, the participants should think carefully about whether the results really make sense.

*Write a clear justification for any research priorities identified during the Gap Analysis.*
In the DRERIP approach, "attributes of each linkage will be defined according to" the direction of the effect, the understanding underlying the effect, the relative magnitude of the effect, and the independence of the effect, acts as kind of a filter. This approach, like summary statistics, acts as a kind of filter. The results may be easier to think about, particularly for people not versed in the biology and hydrology, but information is lost in the process. Justifying any research priorities simply in terms of how they score in the DRERIP framework will leave the rationale for the priorities obscure.

*Write in plain English.*
I found the language in the Gap Analysis Proposal very hard to understand. It is characterized by jargon, nouns used as adjectives, and over-use of various forms of the word "link," such that we have "linkages linked." The proposal is also poorly organized. Such writing serves no good purpose, and the CSAMP would do well to hire a copy editor.

*Be forthcoming about the RPAs.*
The RPAs are central to the whole CSAMP process, but appear in the Gap Analysis only indirectly, in the SST scope, which says that "(T)he results are intended to contribute information relevant to the ESA consultation on the Long Term Operation of the CVP and SWP." The Progress Report is more explicit, for example with the language that "The CAMT's intent is to ensure that disagreement about the basis for and effectiveness of the RPAs be addressed by a science-based process that is legitimate, credible, and relevant to stakeholder concerns." Based on my experience, concern about the RPAs will affect the behavior of the participants in the SST, despite solemn promises to leave stakeholder hats at the door, and I suspect that it would be helpful to be more forthcoming about RPAs in the gap analysis.

**Responses to the review questions:**

*Is the outlined approach sound and reasonable to ensure objective, transparent and comprehensive review of the state of the science regarding water project-linked effects on juvenile salmonid survival in the South Delta?*

I am concerned that it will not. I think the approach will produce a transparent and objective listing of the evidence relevant to the usual suspects, but I do not think that the evidence will be well synthesized, and I do not think the approach will ensure that the review be comprehensive. Rather, as explained above, I think the approach will lead to too narrow a focus.

*Is the process likely to succeed in documenting scientifically well supported linkages, describing key scientific uncertainties and identifying research gaps? Will it support collaborative science?*

My answer is essentially the same as for the previous question. I am concerned that the process will take too narrow a view of the issues, and so miss key scientific uncertainties and research gaps. In particular, I am surprised that the Gap Analysis Proposal does not deal with the applicability of the results of studies using hatchery fish to naturally produced fish, since this issue is identified in Table 3-3 of the Progress Report. I do not have an opinion whether the process will encourage people to collaborate.

*Are there some novel ways the research team should consider for presenting the results?*

The research team might consider using Bayesian Networks (BNs), which can be described crudely as quantified conceptual models, although it may well decide that using BNs would take more time than is available. I became interested in BNs while looking for better methods for environmental flow assessment, and although I did not have an opportunity to actually use them, I think they are a promising approach. I described BNs as follows in Williams (2011), and suggest Appendix A of Hart and Pollino (2009) as a good introduction to them. I am also sending separately the entry on BNs from the Encyclopedia of Statistics in Quality & Reliability.

> Bayesian networks are quantitative models with graphical interfaces that resemble familiar "boxes and arrows" conceptual models. However, as implemented with available software, they also have flexible data management capabilities and algorithms to estimate the probability that some variable will be in a particular state, depending on the state of other variables linked to it through the network. Mathematically, they are directed acyclic graphs. BNs were developed in the field of artificial intelligence, particularly for diagnostic tasks (e.g., what are the probabilities that a patient has one or another disease, conditional on the patient's symptoms and history), but have found application in fields ranging from environmental assessment to criminology to medicine (Marcot et al. 2001, Steventon 2008, Pourret et al. 2008). Applications of BNs to environmental assessments have mostly concerned wildlife, but have been applied to environmental flow assessments especially in Australia (Reiman et al. 2001, Hart and Polino 2009, Shenton et al. 2010, Stewart-Koster et al. 2010). Appendix A of Hart and Pollino (2009) provides an excellent description of BNs, including their limitations. Because the models have simple graphical representations, they have proved useful and effective in group processes,

including those involving stakeholders with conflicting interests (Marcot et al. 2006, Steventon 2008).

*What are the key areas of research team's technical expertise that would be essential for the successful completion of the proposed work?*

If the research team decides to pursue Bayesian Networks, having an expert on their use on the team or available as staff to the team would be essential.

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Appendix 1: Excerpt from Ch. 1 of Williams (2006), Central Valley Salmon:

**Conceptual foundations**

As described by Lichatowich (1998:3), “A conceptual foundation is a set of scientific theories, principles and assumptions, which in aggregate describe how a salmonid-producing ecosystem functions. The conceptual foundation determines how information is interpreted, what problems are identified, and as a consequence also determines the range of appropriate solutions (ISG 1996).”[5] This is similar to what in CALFED parlance is called a conceptual model, but avoids using the word ‘model,’ which has such a range of meanings that its use seems to confuse things more than clarify them.

For most of the twentieth century, management of fish and wildlife had a utilitarian foundation, so that, for example, before passage of the California Environmental Quality Act and other environmental legislation, the basic job of the Department of Fish and Game was to see to it that there were animals for people to harvest for recreation, food, or profit. The conceptual foundation of fisheries management was basically agricultural (Bottom 1997), to the extent that natural production of fish was sometimes referred to as "aquiculture" (e.g., Hatton 1940:334), and the number of salmon that return to spawn is generally called the “escapement,” as if harvest were the right and proper fate of a salmon. Nevertheless, the attitude early in the century seemed to be that one had to understand the biology of an animal in order to manage it. For example, Snyder (1928:25) wrote that: “Believing that measures intended to conserve a fishery can not be intelligently devised and applied until the life history of the species is well known, an investigation of California salmon was begun some years ago, and is still in progress.” Thus, questions of basic biology received attention along with matters of more immediate management concern. This attitude is expressed perhaps most strongly in the many studies of sardines by biologists for the California Department of Fish and Game (CDFG) that are published in various early CDFG Fish Bulletins or issues of California Fish and Game, but it is also apparent in early salmon studies by Rutter (1904), Scofield (1913), Rich (1920), Clark (1928), and Snyder 1921; 1923; 1924a,b,c; 1928), and in the work on steelhead by Shapovalov and Taft (1954, but actually conducted in the 1930s).

Starting in the late 1930s, the main thrust of salmon investigations in the Central Valley seems oriented less toward answering basic biological questions and more toward coping with the consequences of civil works projects such as the Central Valley Project (CVP, e.g., Hatton 1940; Hatton and Clark 1942; Clark 1943), debris dams constructed to allow resumption of hydraulic mining (Sumner and Smith 1940), local irrigation diversions (Hallock and Van Woert 1959), and later the State Water Project (SWP, e.g., Sasaki 1966). Ecologically-oriented studies of the Estuary that were highly advanced for their time began in the 1960s, but were directed primarily toward striped bass, and gave surprisingly little attention to salmon. As described in Ch. 5, it was concluded from monitoring studies at the time that juvenile salmon migrated rapidly through the Delta, so studies of habitat use in the Delta by juvenile salmon apparently

[5] This was an earlier version of ISG (2000), Return to the River.

were regarded as unnecessary, and subsequent studies focused on the survival of smolts migrating through the Delta. Dam construction raised the question of how much water should be released to provide habitat for fish, and “instream flow studies” became a focus of effort, particularly after the development of the Instream Flow Incremental Methodology in the late 1970s and after the legal status of instream resources improved with the 1983 *Audubon v. Superior Court* decision of the California Supreme Court (Appendix C).

Coping with the consequences of civil works projects, and questions relating to hatchery and fisheries management, are still the principal concerns of salmon studies in the Central Valley, although the current emphasis on environmental restoration has increased the level of interest in more basic questions about biological diversity and habitats. The funding for this review is one manifestation of the renewed interest in basing management on better understanding of species of concern and of the ecosystems that support them. As noted earlier, this review takes as a premise that populations together with their environments are the proper subject of concern and of management (Healey and Prince 1995), which requires that attention be given to habitats and to historical changes in habitats, as well as to the populations and historical changes in their abundances and their genomes. The application of this point of view to estuaries, and the reasons for taking it, have been elaborated recently in a major report on the Columbia River Estuary (Bottom et al. 2005).[6]

Bottom et al. (2005, Ch. 2) argued that the utilitarian foundation of early salmon management resulted in "production thinking," a point of view that "... measured success by the output on natural resources (e.g., pounds or numbers of salmon, angler-days of use, etc.)" and "emphasized short-term changes in the abundance of salmon, which were defined arbitrarily as any geographic unit of management interest (e.g., river basin, state, nation)."  As an alternative, Bottom et al. (2005) argued for what they call "population thinking," which they contrast with production thinking in a table, reproduced below. The emphasis is on local populations, diversity in life history patterns, and the varied habitats that support different life history patterns. Although it is applied in this instance to a single genus, it is apparent from the table that population thinking as advocated by Bottom et al. (2005) is consistent with CALFED's emphasis on ecosystem restoration. Bottom et al. (2005) were concerned with the Columbia River Estuary, and the bottom two rows of Table 1.1 are specific to estuaries, but it is easy to generalize them to include upstream habitats as well. The third row in the comparison, time-frame, deserves emphasis. Recent work has demonstrated that salmon, like other organisms, can evolve significantly within a few generations in response to translocation, hatchery culture, and harvest (Kinnison and Hendry 2004 and citations therein). Accordingly, habitat restoration and management should take an evolutionary perspective (Ashley et al. 2003).

Table 1-1. Comparison of production thinking and population thinking, reproduced from Table 2.1 in Bottom et al. (2005), *Salmon at River's End*.

[6] Bottom et al. (2005) has been available for several years as a draft, and may be cited elsewhere as Bottom et al. (2001).

| | Production Thinking | Population Thinking |
|---|---|---|
| Goals | **Efficiency, production** | **Resilience, reproduction** |
| Population Units | **Arbitrarily defined** | **Biologically defined** |
| Time Frame | **Short** | **Evolutionary** |
| Objectives | **Control survival and abundance** | **Conserve local populations and life-history diversity** |
| Estuary Function | **Corridor for a single, homogenous group of salmon** | **Nursery area for many self-sustaining populations** |
| Estuary Management | **Control predators, promote rapid salmon out-migration** | **Protect habitats of diverse life-history types** |

A recent report on salmon monitoring (Botkin et al. 2000) demonstrates the importance of making conceptual foundations explicit. Botkin et al. (2000) is the report of a distinguished panel that addressed the following question: “If actions are taken in an attempt to improve the status of salmon (or a specific stock of salmon), what measurements are necessary, feasible, and practical to determine whether the actions are successful?” It appears that the report is in large part a reaction to an argument that because of the difficulties in estimating salmon abundance, assessments of management actions such as timber harvest could be made entirely on the basis of data on habitat conditions. In emphasizing the importance of estimates of abundance in reaction to that argument, however, the panel implicitly, and perhaps inadvertently, adopted a strong production perspective, and says almost nothing about the importance of diversity in life histories.

Population thinking as defined by Bottom et al. (2005) is approximately the conceptual foundation for the CALFED Ecosystem Restoration Program. In the Central Valley, however, much of local salmon management still embodies production thinking, although concern for meeting numerical goals for harvest and escapement has been largely superceded by concern for not exceeding numerical limits for take of listed species at the CVP and SWP pumps. For example, the passages cited above squarely apply to the 1993 Biological Opinions for the Operation of the CVP and SWP (NMFS 1993) and to the report of the Sacramento River Fall Chinook Review Team (SRFCRT 1994). The Review Team was formed "to determine why the escapement goals for Sacramento River fall chinook (SRFC) were not met in 1990-1992, and to recommend actions to assure future productivity of the stock;" the review team concluded in part (p. 1) that:

> Because it is unlikely that we can affect ocean survival,[7] the most effective means of increasing adult abundance is to increase the number of juvenile salmon entering the ocean. ... The most efficient and effective way to increase juvenile abundance would be to increase survival during outmigration to the ocean, particularly during passage through the Sacramento-San Joaquin Delta. ... Any improvements in delta survival

[7] This seems a curious statement in a report published by an agency involved in the control of ocean harvest.

would benefit natural production at a life stage when natural mortality is not density dependent and would result in a commensurate increase in adults if ocean survival is independent of freshwater survival.

Perhaps the most striking consequence of production thinking regarding salmon in the Central Valley is the lack of good data on the proportion of spawning adults that were naturally or hatchery produced. Unless Central Valley salmon were regarded as interchangeable, distinguishing hatchery and naturally produced fish would seem of prime importance. The limited attention given to the Delta as rearing habitat for juvenile chinook is probably another consequence. The point is not that production thinking is wrong, but that it is limited in ways that tend to undercut objectives for restoration, even when the objectives are embodied in legislation such as the Central Valley Project Improvement Act or the Endangered Species Act.

A conceptual foundation that is somewhat different from but complementary to that of Bottom et al. (2005) has been described for the Columbia Basin in "Return to the River" (ISG 2000), a report by the Independent Scientific Group for the Northwest Power and Conservation Council.[8] The critical elements of the conceptual foundation that they suggest are, slightly modified (their Box 3.1):

1. Restoration of the [Central Valley] salmonids must address the entire natural and cultural ecosystem, which encompasses the continuum of freshwater, estuarine, and ocean habitats where salmonid fishes complete their life histories. This consideration includes human developments, as well as natural habitats.

2. Sustained salmonid productivity requires a network of complex and interconnected habitats, which are created, altered, and maintained by natural physical processes in freshwater, the estuary, and the ocean. These diverse and high-quality habitats, which have been extensively degraded by human activities, are crucial for salmonid spawning, rearing, migration, maintenance of food webs, and predator avoidance. Ocean conditions, which are variable, are important in determining the overall patterns of productivity of salmon populations.

3. Life history diversity, genetic diversity, and metapopulation organization are ways that salmonids adapt to their complex and connected habitats. These factors are the basis of salmonid productivity and contribute to the ability of salmonids to cope with environmental variation that is typical of freshwater and marine environments.

Frissell et al. (1997) provide another good discussion of the conceptual foundations of salmon management, contrasting what they call the "Production/exploitation" and "Ecosystem/restoration" views. Again, the language is somewhat different, but the essential message is the same.

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[8] This is available at http://www.nwcouncil.org/library/return/2000-12.htm, as of 3/06; select ch. 3.

The implicit expectation in articulating a conceptual foundation (or a conceptual model) is that it will lead to ways of thinking and acting that are more likely to result in successful restoration actions, or in studies that will be useful for guiding or evaluating such restoration. However, there is good reason to maintain a critical attitude toward this proposition. Thirty-five years ago, Don Kelley (1968) ended the summary chapter of a major report to the Bay-Delta Water Quality Control Program with a discussion of the need to develop better understanding of the factors influencing fish and wildlife populations in the Estuary:

> ... The systems analysis approach described by K. E. F. Watt (1966, 1968) may provide the most useful means of developing that understanding to date. This method involves developing conceptual models like those drawn by the authors of subsequent chapters in this report, using them to sort out the variables that most influence the resource and finally the development of simulation models describing what affects each major resource. This method offers an excellent means of making certain that data collecting on animal populations is relevant and can be fitted together so that the end result is real understanding of the influence of future environmental change.

Two lessons can be drawn from Kelley's observation. First, it is not enough to have a firm conceptual foundation or coherent conceptual models; to the extent that conceptual models or foundations guide inquiries, they can mislead as well as lead. For example, it is not clear that the conceptual foundations reviewed above adequately frame the challenges posed by anthropogenic climate change. Second, there seems to be a human tendency to imagine that the most recently developed approach will soon yield a major breakthrough in understanding. Based on historical experience, the odds are against this. We need to act, in studies as well as in management, based on the information and concepts that we have available to us, but we should keep in mind the favorite motto of a certain 19th Century German philosopher, disastrously ignored by his followers: *De omnibus dubitandum.*[9]

[9] Doubt everything. (G. Seldes, 1960, *The Great Quotations*. Lyle Stuart, New York.)

# Bayesian Networks

## Introduction

Bayesian networks (BNs), also known as *belief networks* (or Bayes nets for short), belong to the family of probabilistic *graphical models* (GMs). These graphical structures are used to represent knowledge about an uncertain domain. In particular, each node in the graph represents a random variable, while the edges between the nodes represent probabilistic dependencies among the corresponding random variables. These conditional dependencies in the graph are often estimated by using known statistical and computational methods. Hence, BNs combine principles from graph theory, **probability theory**, computer science, and statistics.

GMs with *undirected edges* are generally called *Markov random fields* or *Markov networks*. These networks provide a simple definition of independence between any two distinct nodes based on the concept of a *Markov blanket*. Markov networks are popular in fields such as statistical physics and computer vision [1, 2].

BNs correspond to another GM structure known as a *directed acyclic graph* (DAG) that is popular in the statistics, the machine learning, and the artificial intelligence societies. BNs are both mathematically rigorous and intuitively understandable. They enable an effective representation and computation of the joint probability distribution (JPD) over a set of random variables [3].

The structure of a DAG is defined by two sets: the set of nodes (vertices) and the set of directed edges. The nodes represent random variables and are drawn as circles labeled by the variable names. The edges represent direct dependence among the variables and are drawn by arrows between nodes. In particular, an edge from node $X_i$ to node $X_j$ represents a statistical dependence between the corresponding variables. Thus, the arrow indicates that a value taken by variable $X_j$ depends on the value taken by variable $X_i$, or roughly speaking that variable $X_i$ "influences" $X_j$. Node $X_i$ is then referred to as a *parent* of $X_j$ and, similarly, $X_j$ is referred to as the *child* of $X_i$. An extension of these genealogical terms is often used to define the sets of "descendants" – the set of nodes that can be reached on a direct path from the node, or "ancestor" nodes – the set of nodes from which the node can be reached on a direct path [4]. The structure of the acyclic graph guarantees that there is no node that can be its own ancestor or its own descendent. Such a condition is of vital importance to the factorization of the joint probability of a collection of nodes as seen below. Note that although the arrows represent direct causal connection between the variables, the *reasoning process* can operate on BNs by propagating information in any direction [5].

A BN reflects a simple conditional independence statement. Namely that each variable is independent of its nondescendents in the graph given the state of its parents. This property is used to reduce, sometimes significantly, the number of parameters that are required to characterize the JPD of the variables. This reduction provides an efficient way to compute the posterior probabilities given the evidence [3, 6, 7].

In addition to the DAG structure, which is often considered as the "qualitative" part of the model, one needs to specify the "quantitative" parameters of the model. The parameters are described in a manner which is consistent with a Markovian property, where the conditional probability distribution (CPD) at each node depends only on its parents. For discrete random variables, this conditional probability is often represented by a table, listing the local probability that a child node takes on each of the feasible values – for each combination of values of its parents. The joint distribution of a collection of variables can be determined uniquely by these local conditional probability tables (CPTs).

Following the above discussion, a more formal definition of a BN can be given [7]. A Bayesian network $B$ is an annotated acyclic graph that represents a JPD over a set of random variables $\mathbf{V}$. The network is defined by a pair $B = \langle G, \Theta \rangle$, where $G$ is the DAG whose nodes $X_1, X_2, \ldots, X_n$ represents random variables, and whose edges represent the direct dependencies between these variables. The graph $G$ encodes independence assumptions, by which each variable $X_i$ is independent of its nondescendents given its parents in $G$. The second component $\Theta$ denotes the set of parameters of the network. This set contains the parameter $\theta_{x_i|\pi_i} = P_B(x_i|\pi_i)$ for each realization $x_i$ of $X_i$ conditioned on $\pi_i$, the set of parents of $X_i$ in $G$. Accordingly, $B$ defines a unique JPD over $\mathbf{V}$, namely:

Ben-Gal I., Bayesian Networks, in Ruggeri F., Faltin F. & Kenett R.,
Encyclopedia of Statistics in Quality & Reliability, Wiley & Sons (2007).

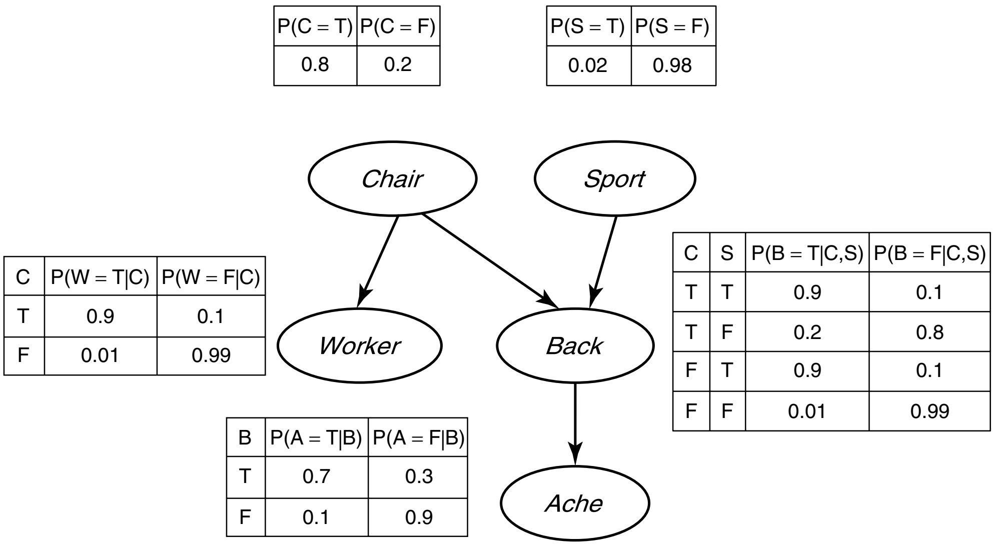


$$P_B(X_1, X_2, \ldots, X_n) = \prod_{i=1}^{n} P_B(X_i|\pi_i) = \prod_{i=1}^{n} \theta_{X_i|\pi_i} \tag{1}$$

For simplicity of representation we omit the subscript $B$ henceforth. If $X_i$ has no parents, its local probability distribution is said to be *unconditional*, otherwise it is *conditional*. If the variable represented by a node is *observed*, then the node is said to be an evidence node, otherwise the node is said to be hidden or latent.

Consider the following example that illustrates some of the characteristics of BNs. The example shown in Figure 1 has a similar structure to the classical "earthquake" example in Pearl [3]. It considers a person who might suffer from a back injury, an event represented by the variable *Back* (denoted by B). Such an injury can cause a backache, an event represented by the variable *Ache* (denoted by A). The back injury might result from a wrong sport activity, represented by the variable *Sport* (denoted by S) or from new uncomfortable chairs installed at the person's office, represented by the variable *Chair* (denoted by C). In the latter case, it is reasonable to assume that a coworker will suffer and report a similar backache syndrome, an event represented by the variable *Worker* (denoted by W). All variables are binary; thus, they are either true (denoted by "T") or false (denoted by "F"). The CPT of each node is listed besides the node.

In this example the parents of the variable *Back* are the nodes *Chair* and *Sport*. The child of *Back* is *Ache*, and the parent of *Worker* is *Chair*. Following the BN independence assumption, several independence statements can be observed in this case. For example, the variables *Chair* and *Sport* are marginally independent, but when *Back* is given they are conditionally dependent. This relation is often called *explaining away*. When *Chair* is given, *Worker* and *Back* are conditionally independent. When *Back* is given, *Ache* is conditionally independent of its ancestors *Chair* and *Sport*. The conditional independence statement of the BN provides a compact factorization of the JPDs. Instead of factorizing the joint distribution of all the variables by the chain rule, i.e., P(C,S,W,B,A) = P(C)P(S|C)P(W|S,C)P(B|W,S,C)P(A|B,W,S,C), the BN defines a unique JPD in a factored form, i.e. P(C,S,W,B,A) = P(C)P(S)P(W|C)P(B|S, C)P(A|B). Note that the BN form reduces the number of the model parameters, which belong to a multinomial distribution in this case, from $2^5 - 1 = 31$ to 10 parameters. Such a reduction provides great benefits from inference, learning (parameter **estimation**), and computational perspective. The resulting model is more robust with respect to **bias**-variance effects [8]. A practical graphical criterion that helps to




| P(C = T) | P(C = F) |
|---|---|
| 0.8 | 0.2 |

| P(S = T) | P(S = F) |
|---|---|
| 0.02 | 0.98 |

| C | P(W = T\|C) | P(W = F\|C) |
|---|---|---|
| T | 0.9 | 0.1 |
| F | 0.01 | 0.99 |

| C | S | P(B = T\|C,S) | P(B = F\|C,S) |
|---|---|---|---|
| T | T | 0.9 | 0.1 |
| T | F | 0.2 | 0.8 |
| F | T | 0.9 | 0.1 |
| F | F | 0.01 | 0.99 |

| B | P(A = T\|B) | P(A = F\|B) |
|---|---|---|
| T | 0.7 | 0.3 |
| F | 0.1 | 0.9 |

**Figure 1** The backache BN example

investigate the structure of the JPD modeled by a BN is called *d-separation* [3, 9]. It captures both the conditional independence and dependence relations that are implied by the Markov condition on the random variables [2].

## Inference via BN

Given a BN that specified the JPD in a factored form, one can evaluate all possible inference queries by marginalization, i.e. summing out over "irrelevant" variables. Two types of inference support are often considered: *predictive support* for node $X_i$, based on evidence nodes connected to $X_i$ through its parent nodes (also called *top-down reasoning*), and *diagnostic support* for node $X_i$, based on evidence nodes connected to $X_i$ through its children nodes (also called *bottom-up reasoning*). Given the example in Figure 1, one might consider the diagnostic support for the belief on new uncomfortable chairs installed at the person's office, given the observation that the person suffers from a backache. Such a support is formulated as follows:

$$\mathrm{P(C = T|A = T)} = \frac{\mathrm{P(C = T,\ A = T)}}{\mathrm{P(A = T)}} \tag{2}$$

where

$$\begin{aligned}\mathrm{P(C = T,\ A = T)} &= \sum_{\mathrm{S,W,B}\in\{\mathrm{T,F}\}} \mathrm{P(C = T)P(S)} \\ &\quad \times \mathrm{P(W|C = T)P(B|S,\ C = T)P(A = T|B)}\end{aligned} \tag{3}$$

and

$$\begin{aligned}\mathrm{P(A = T)} &= \sum_{\mathrm{S,W,B,C}\in\{\mathrm{T,F}\}} \mathrm{P(C)P(S)P(W|C)P(B|S,C)} \\ &\quad \times \mathrm{P(A = T|B)}\end{aligned} \tag{4}$$

Note that even for the binary case, the JPD has size $\mathrm{O}(2^n)$, where $n$ is the number of nodes. Hence, summing over the JPD takes exponential time. In general, the full summation (or integration) over discrete (continuous) variables is called *exact inference* and known to be an *NP-hard problem*. Some efficient algorithms exist to solve the exact inference problem in restricted classes of networks. One of the most popular algorithms is the *message passing algorithm* that solves the problem in $\mathrm{O}(n)$ steps (linear in the number of nodes) for *polytrees* (also called *singly connected networks*), where there is at most one path between any two nodes [3, 5]. The algorithm was extended to general networks by Lauritzen and Spiegelhalter [10]. Other exact inference methods include the *cycle-cutset* conditioning [3] and variable elimination [11].

*Approximate inference* methods were also proposed in the literature, such as ***Monte Carlo*** sampling that gives gradually improving estimates as sampling proceeds [9]. A variety of standard ***Markov chain Monte Carlo*** (MCMC) methods, including the *Gibbs sampling* and the *Metropolis–Hastings algorithm*, were used for approximate inference [4]. Other methods include the *loopy belief propagation* and *variational methods* [12] that exploit the **law of large numbers** to approximate large sums of random variables by their means.

## BN Learning

In many practical settings the BN is unknown and one needs to learn it from the data. This problem is known as the *BN learning problem*, which can be stated informally as follows: Given training data and prior information (e.g., **expert knowledge**, **casual relationships**), estimate the graph topology (network structure) and the parameters of the JPD in the BN.

Learning the BN structure is considered a harder problem than learning the BN parameters. Moreover, another obstacle arises in situations of *partial observability* when nodes are hidden or when data is missing. In general, four BN learning cases are often considered, to which different learning methods are proposed, as seen in Table 1 [13].

In the first and simplest case the goal of learning is to find the values of the BN parameters (in each CPD) that maximize the (log)likelihood of the training

**Table 1** Four cases of BN learning problems

| Case | BN structure | Observability | Proposed learning method |
|---|---|---|---|
| 1 | Known | Full | Maximum-likelihood estimation |
| 2 | Known | Partial | EM (or gradient ascent), MCMC |
| 3 | Unknown | Full | Search through model space |
| 4 | Unknown | Partial | EM + search through model space |

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dataset. This dataset contains $m$ cases that are often assumed to be independent. Given training dataset $\mathbf{\Sigma} = \{\mathbf{x_1}, \ldots, \mathbf{x_m}\}$, where $\boldsymbol{x_l} = (x_{l1}, \ldots, x_{ln})^T$, and the parameter set $\mathbf{\Theta} = (\boldsymbol{\theta}_\mathbf{1}, \ldots, \boldsymbol{\theta}_\mathbf{n})$, where $\boldsymbol{\theta}_i$ is the vector of parameters for the conditional distribution of variable $X_i$ (represented by one node in the graph), the log-likelihood of the training dataset is a sum of terms, one for each node:

$$\log L(\Theta|\Sigma) = \sum_m \sum_n \log P(x_{li}|\pi_i, \theta_i) \qquad (5)$$

The log-likelihood scoring function *decomposes* according to the graph structure; hence, one can maximize the contribution to the log-likelihood of each node independently [14]. Another alternative is to assign a prior **probability density function** to each parameter vector and use the training data to compute the posterior parameter distribution and the Bayes estimates. To compensate for zero occurrences of some sequences in the training dataset, one can use appropriate (mixtures of) conjugate prior distributions, e.g. the Dirichlet prior for the multinomial case as in the above backache example or the Wishart prior for the Gaussian case. Such an approach results in a maximum *a posteriori* estimate and is also known as the *equivalent* ***sample size*** (ESS) method.

In general, the other learning cases are computationally intractable. In the second case with known structure and partial observability, one can use the **EM (expectation maximization) algorithm** to find a locally optimal maximum-likelihood estimate of the parameters [4]. MCMC is an alternative approach that has been used to estimate the parameters of the BN model. In the third case, the goal is to learn a DAG that best explains the data. This is an NP-hard problem, since the number of DAGs on $N$ variables is superexponential in $N$. One approach is to proceed with the simplest assumption that the variables are conditionally independent given a class, which is represented by a single common parent node to all the variable nodes. This structure corresponds to the *naïve BN*, which surprisingly is found to provide reasonably good results in some practical problems. To compute the Bayesian score in the fourth case with partial observability and unknown graph structure, one has to marginalize out the hidden nodes as well as the parameters. Since this is usually intractable, it is common to use an asymptotic approximation to the posterior called *Bayesian information criterion* (BIC) also known as the *minimum description length* (MDL) approach. In this case one considers the trade-off effects between the likelihood term and a penalty term associated with the model complexity. An alternative approach is to conduct local search steps inside of the M step of the EM algorithm, known as *structural EM*, that presumably converges to a local maximum of the BIC score [7, 13].

## BN and Other Markovian Probabilistic Models

It is well known that classic machine learning methods like Hidden Markov models (HMMs), **neural networks**, and Kalman filters can be considered as special cases of BNs [4, 13] Specific types of BN models were developed to address stochastic processes, known as *dynamic BN*, and counterfactual information, known as *functional BN* [5]. Ben-Gal *et al.* [8] defined a hierarchical structure of Markovian GMs, which we follow here. The structure is described within the framework of DNA sequence classification, but is relevant to other research areas. The authors introduce the *variable-order Bayesian network* (VOBN) model as an extension of the *position weight matrix* (PWM) model, the *fixed-order Markov model* (MM) including HMMs, the *variable-order Markov* (VOM) model, and the BN model.

The PWM model is presumably the simplest and the most common context-independent model for DNA sequence classification. The basic assumption of the PWM model is that the random variables (e.g., nucleotides at different positions of the sequence) are statistically independent. Since this model has no memory it can be regarded as a fixed-order MM of order 0. In contrast, higher fixed-order models, such as MMs, HMMs, and interpolated MMs, rely on the statistical dependencies within the data to indicate repeating motifs in the sequence.

VOM models stand in between the above two types of models with respect to the number of model parameters. In fact, VOM models do not ignore statistical dependencies between variables in the sequence, yet, they take into account only those dependencies that are statistically significant. In contrast to fixed-order MMs, where the order is the same for all positions and for all contexts, in VOM models the order may vary for each position, based on its contexts.

Unlike the VOM models, which are homogeneous and which allow statistical dependences only between

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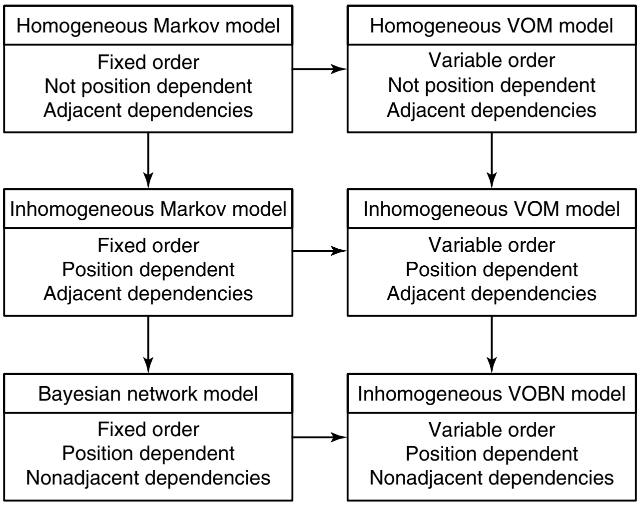


**Figure 2** Hierarchical structure of Markovian graphical models [© OUP, 2005.]

adjacent variables in the sequence, VOBN models are inhomogeneous and allow statistical dependences between nonadjacent positions in a manner similar to BN models. Yet, as opposed to BN models, where the order of the model at a given node depends only on the size of the set of its parents, in VOBN models the order also depends on the context, i.e. on the specific observed realization in each set of parents. As a result, the number of parameters that need to be estimated in VOBN models is potentially smaller than in BN models, yielding a smaller chance for overfitting of the VOBN model to the training dataset. Context-specific BNs (e.g., [15, 16]) are closely related to, yet constructed differently from, the VOBN models [8].

To summarize, the VOBN model can be regarded as an extension of PWM, fixed-order Markov, and BN models as well as VOM models in the sense that these four models are special cases of the VOBN model. This means that in cases where statistical dependencies are insignificant, the VOBN model degenerates to the PWM model. If statistical dependencies exist only between adjacent positions in the sequence and the memory length is identical for all contexts, the VOBN model degenerates to an inhomogeneous fixed-order MM. If, in addition, the CPDs are identical for all positions, the VOBN model degenerates to a homogeneous fixed-order MM. If the memory length for a given position is identical for all contexts and depends only on the number of parents, the VOBN model degenerates to a BN model. If the context-dependent statistical dependencies in the VOBN model are restricted to adjacent positions, the VOBN model degenerates to the inhomogeneous VOM model. If, in addition, the context-dependent CPDs are identical for all positions, the VOBN model degenerates to a homogeneous VOM model. Figure 2 sketches these relationships between fixed-order MMs, BN models, VOM models, and VOBN models.

## Summary

BNs became extremely popular models in the last decade. They have been used for applications in various areas, such as machine learning, text mining, natural language processing, speech recognition, signal processing, bioinformatics, error-control codes, medical diagnosis, weather forecasting, and cellular networks.

The name BNs might be misleading. Although the use of Bayesian statistics in conjunction with BN provides an efficient approach for avoiding data overfitting, the use of BN models does not necessarily imply a commitment to Bayesian statistics. In fact, practitioners often follow frequentists' methods to estimate the parameters of the BN. On the other hand, in a general form of the graph, the nodes can represent not only random variables but also hypotheses, beliefs, and latent variables [13]. Such a structure is intuitively appealing and convenient for the representation of both causal and probabilistic semantics. As indicated by David [17], this structure is ideal for combining prior knowledge, which often comes in causal form, and observed data. BN can be used, even in the case of missing data, to learn the causal relationships and gain an understanding of the various problem domains and to predict future events.

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