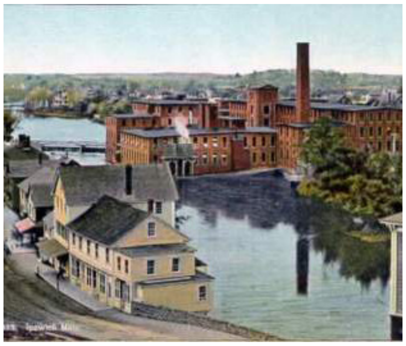
Metropolitan Area Planning Council, acting
on behalf of the North Shore Water Resilience
Task Force

Final Report
July 2025

Assessment of Water Supply Alternatives Using the New Ipswish River Streamflow and Watershed Analysis Model (IRSWAM)



Horsley Witten Group
Sustainable Environmental Solutions

Weston & Sampson

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

*Scenarios 0A vs. Scenario 0B (Original vs. Updated GW Withdrawals)

LIST OF APPENDICES

1.0 EXECUTIVE SUMMARY

The Horsley Witten–Weston & Sampson team ("the project team") was contracted by the North Shore Water Resilience Task Force (the Task Force) to develop a spreadsheet-based, mass balance model of the Ipswich River watershed ("the model") to support an evaluation of the relative benefits of several, Task Force selected, planning level, water supply alternatives for increasing streamflow and resilience. The watershed includes 22 cities and water withdrawn from the watershed serves a population significantly greater than the population who actually live there, creating a significant net water export from the basin. Compounding the significant net export problem, the watershed also has a relatively low percentage of sand and gravel aquifer material and relatively high rates of stormwater runoff and evapotranspiration that together limit the amount of water available for aquifer recharge and storage to supply sustained baseflow during extended periods of low precipitation. The baseflow capacity at the sub-basin level can sometimes be significantly less than is the case for the larger watershed.

The project team developed the Ipswich River Streamflow and Watershed Analysis Model (IRSWAM) to evaluate the Task Force selected water supply alternatives against each other from the perspective of improving river flow conditions overall, and for as many sub-basins as possible. IRSWAM is a regional, mass-balance model that is built upon the methodology of the Water Management Act (WMA) tool, developed by the Massachusetts Department of Environmental Protection (MassDEP) to guide MassDEP's permitting process for new water withdrawals under the WMA relative to specific metrics which help define the impacts of water management practices on the environment - Biological Category (BC), Groundwater Withdrawal Criteria (GWC), Net Groundwater Depletion (NGD), and August median flow seasonal criteria. Given that these WMA metrics provide existing quantifiable criteria and regulatory framework in which sub-basins can be evaluated, the metrics and the WMA Tool serve as the logical foundation from which IRSWAM was created.

Please note that our use of these WMA metrics does not connote any regulatory implications. Rather, the WMA metrics used are a familiar set of criteria with which to evaluate the modeled impacts of different water supply alternatives from a planning perspective. MassDEP has and will continue to rely on the changes to individual subbasin's GWC and BC when evaluating WMA permit applications. In addition, the BC and GWC metrics, as defined under SWMI, are categorical rather than mathematical metrics (i.e., those metrics exist as distinct whole number values between 1 and 5; there is no such thing as a GWC 2.3 for example). Each category represents a range of underlying flow alteration values, so they cannot be truly "averaged". In fact, depending on where within each category's range of flow alteration values fall, averaging could result in skewed conclusions. Watershed-wide averages may also obscure more severe alterations in specific subbasins. However, for the purposes of this IRSWAM modeling project and summary report, BC and GWC subbasin metrics are averaged (using decimal values) across the entire watershed for each scenario in order to characterize the modeled effects of water supply scenarios at a larger scale. Comparing individual subbasin BC and GWC modeled values and changes in watershed-wide average BC and GWC allows for more nuance when comparing water supply scenarios.

Some of the key features of IRSWAM are:

- Updating the public groundwater withdrawal data underlying the WMA Tool to reflect significant changes that have occurred over the past two decades.
- Providing the ability to add or remove withdrawals in one or more sub-basins simultaneously and allowing new or existing sources to be operated seasonally.
- Producing model results by sub-basin, as well as cumulatively in all downstream sub-basins.
- Evaluating the impact of potential water supply alternative scenarios to WMA metrics.
- Evaluating the impact of surface or groundwater withdrawals and discharges on August median flow conditions throughout the watershed.

IRSWAM was applied to assess the relative impacts of five Task Force-selected alternative water supply scenarios, as well as a sixth combination scenario, on resultant changes in WMA metrics (i.e. Flow Alteration, GWC, NGD, BC, and other model outputs. IRSWAM is a mass-balance model designed to evaluate the relative, not absolute, impacts associated with water supply alternatives. As such, model inputs and outputs represent a single, typical set of average conditions. The decision to utilize the WMA tool and the Massachusetts Sustainable Yield Estimator (MASYE) estimates included therein as the basis for IRSWAM stems from the effectiveness of those tools and datasets towards the main purpose of IRSWAM for evaluating the relative efficacy of water supply alternatives within the regulatory framework of the WMA.

WATER USE CHANGES SINCE 2004

Since the WMA Tool was built using water use data gathered between 2000 and 2004, the first use of IRSWAM was to evaluate the effects of updating the WMA-regulated groundwater withdrawal data to reflect August average withdrawals between 2018 and 2022 (the most recent complete data available), as tabulated by the Ipswich River Watershed Association (IRWA). Owing to various changes of water use in the watershed, the 2018-2022 watershed-wide total of public groundwater withdrawals is approximately half that of the 2000-2004 WMA Tool values. However, increases in private withdrawals are not represented in the model or considered in this study because they have not been quantified at the subbasin scale.

The watershed-wide WMA metrics and other IRSWAM outputs comparing the original to more recent withdrawals (Scenarios 0A vs. 0B) suggest these public water supply reductions over the past 20 years have resulted in a significant improvement in the modeled streamflows. The watershed-wide average Flow Alteration and Net Groundwater Depletion were both reduced by 26% (from 54% to 28% for Flow alteration and 29% to 3% for Net Groundwater Depletion) (Scenario 0A vs 0B). As a result, the average GWC and a modified version of BC (as explained in more detail in the report) have decreased as well, from 3.40 to 2.82 and from 2.54 to 1.54, respectively. These modeled improvements may be offset by shifts to private well use and reservoir withdrawals that are not captured by the available WMA data behind the WMA Tool and IRSWAM.

WATER SUPPLY ALTERNATIVE SCENARIOS

Six planning level water supply alternatives were identified by the Task Force for evaluation with IRSWAM (Table 4-6). All Scenarios included the elimination of all groundwater (and two selected in-line reservoir) summertime withdrawals for selected communities. The logic behind the selected, relatively extreme scenarios was to evaluate the sensitivity of resultant water resource changes to endpoint scenarios. This allows the Task Force to better identify locations where water use changes would be most effective and then consider implementation considerations relative to these potential relative benefits.

Table 4-6: Water Supply Alternatives			
Scenario	Supplier(s)	Sources Affected	Combined Withdrawals (MGD)
1	Wilmington	PWS-3342000-11G, PWS-3342000-12G, PWS-3342000-13G, PWS-3342000-14G, PWS-3342000-05G, PWS-3342000-06G	1.837
2	Lynnfield	PWS-3164000-02G, PWS-3164000-05G, PWS-3164000-06G, PWS-3164000-07G, PWS-3164000-08G	0.461
3	Danvers-Middleton	PWS-3071000-02G (plus Middleton Pond and Emerson Brook Reservoir)	0.597
4	Topsfield & Ipswich	PWS-3298000-02G, PWS-3144000-04G, PWS-3298000-01G, PWS-3144000-06G, PWS-3144000-07G	0.724
5	Wenham, Hamilton & Ipswich	PWS-3119000-05G, PWS-3119000-06G, PWS-3119000-07G, PWS-3119000-08G, PWS-3320000-01G, PWS-3320000-02G, PWS-3144000-04G, PWS-3144000-07G, PWS-3119000-02G, PWS-3342000-02G	1.265
6	Combined 1, 2, 3, 4, and 5	All of the above	4.637

Each of the six theoretical water supply alternatives were evaluated with IRSWAM and compared against an existing conditions baseline (Scenario 0B) defined with the updated withdrawal data (2018-2022). The model's outputs are summarized at a watershed scale in Tables 4-8A and 4-8B. Modeled changes to flow metrics for any scenario occur within the sub-basin(s) in which the withdrawals are altered and in those hydraulically connected sub-basins downstream of those containing the altered withdrawals (these are generally mainstem segments). No changes to flow metrics are modeled to occur for sub-basins upstream of the altered withdrawals, or for downstream tributary subbasins whose flows are unaffected by the altered withdrawals. The modeled "watershed-wide" averages are derived from the values of both the subbasins affected by the altered withdrawals and those unaffected by the altered withdrawals.

Table 4-8A: Watershed-Wide Weighted Averages of IRSWAM Outputs					
Scenario**	Flow Alteration	GWC	Net GW Depletion	BC	August Median Affected Flow (cfsm)
0B	27.5%	2.82	3.1%	4.48	0.182
1	14.5%	2.12	-10.0%	4.48	0.210
2	26.7%	2.80	2.2%	4.48	0.184
3	27.5%	2.82	3.0%	4.48	0.189
4	25.9%	2.75	1.4%	4.45	0.186
5	21.6%	2.67	-2.9%	4.46	0.194
6	6.0%	1.79	-18.4%	4.37	0.233

Table 4-8B: Change from Baseline in Watershed-Wide Weighted Averages of IRSWAM Outputs					
Scenario**	Δ Flow Alteration*	Δ GWC*	Δ Net GW Depletion*	Δ BC*	Δ August Median Affected Flow (cfsm)
0B	-	-	-	-	-
1	-13.1%	-0.70	-13.1%	-0.00	+0.028 (+15.3%)
2	-0.9%	-0.01	-0.9%	-0.00	+0.002 (+1.1%)
3	-0.1%	0.00	-0.1%	-0.00	+0.007 (+3.6%)
4	-1.7%	-0.07	-1.7%	-0.03	+0.003 (+1.8%)
5	-5.9%	-0.15	-5.9%	-0.02	+0.011 (+6.3%)
6	-21.5%	-1.03	-21.5%	-0.11	+0.051 (+28.0%)

* Percent changes are only provided for August Median Affected Flow. Values for flow alteration and Net GW Depletion reflect the absolute change in the metric, itself a percentage. GWC and BC are unitless quantities which do not reflect logically as percentages. Note that reductions in flow alteration, GWC, Net GW Depletion, and BC reflect increased streamflow.

**Scenario 0B refers to the updated baseline with public drinking water withdrawals estimated from 2018-2022 data. The other scenarios represent the cessation of pumping by town(s) as follows: 1 - Wilmington, 2 – Lynnfield, 3 – Danvers-Middleton, 4 - Topsfield & Ipswich, 5 - Wenham, Hamilton & Ipswich, and 6 – combination of all other scenarios.

As expected, Scenario 6, a combination of the other five scenarios, and its 4.631-MGD reduction in withdrawals produced the greatest improvements, reducing Flow Alteration from 27.5 to 6.0% and as a result would reduce the Groundwater Withdrawal Category from 2.82 to 1.79. Net Groundwater Depletion was reduced from a 3.1% deficit across the watershed to a surplus of 18.4%, improving the Biological Category from 1.54 to 1.00. August Median Affected Flows, as calculated by applying the net change in both groundwater and surface water withdrawals and discharges to the SYE2-identified August median unaffected flows, increased from 0.182 cfsm to 0.233 cfsm, a 28.0% improvement.

Of particular interest is the effectiveness of Scenario 1 on its own. With the highest groundwater pumping reduction among Scenarios 1 through 5 at 1.837 MGD, and the affected wells' location in the headwaters of the Ipswich River watershed, Scenario 1 produces a strong benefit that literally trickles down to and through the rest of the watershed, having an outsized impact. Scenario 1 is responsible for approximately 55% of the improvement to August Median Affected Flows, 60% of the improvement to Flow Alteration and Net Groundwater Depletion, and 70% of the improvement in average GWC and BC categories achieved under the combined Scenario 6, despite representing only 40% of Scenario 6's groundwater withdrawal reductions.

Given the strong correlation between reduced withdrawal rates and benefits to the Ipswich River and its watershed, and the fact that if pumping is reduced that drinking water must be supplied and/or purchased from outside the watershed, it is useful to understand how those benefits compare between scenarios on a per MGD reduced basis. Table 4-9 presents such normalized model outputs for several key outputs. That table can be interpreted as indicative of which scenarios are most efficient or provide literally the greatest "bang" or benefit "for your buck."

Table 4-9: Normalized Watershed and Streamflow Changes

Scenario**	Reduction in Pumping (MGD)	Δ Flow Alteration / Net GW Depletion (%)*	Δ August Median Affected Flow (%)*
0B	---	---	---
1	1.837	7.1%	8.3%
2	0.461	1.9%	2.5%
3	0.597	0.1%	6.0%
4	0.724	2.3%	2.6%
5	1.265	4.7%	5.0%
6	4.637	4.6%	6.0%

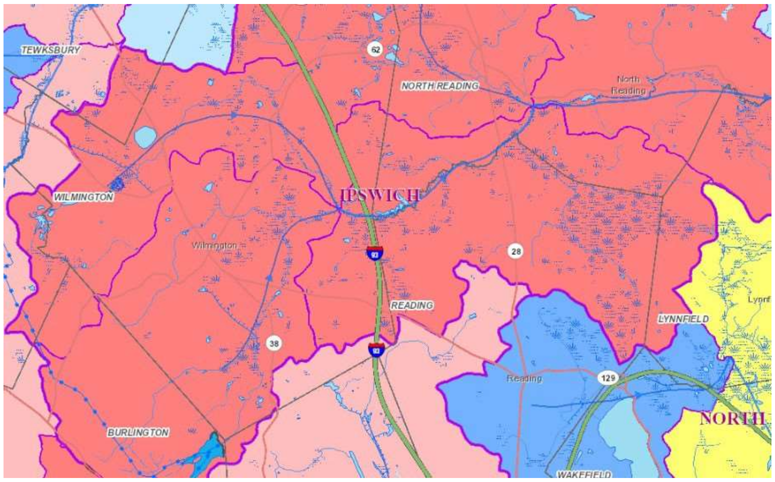
*Changes were divided by each scenario's total reduction in groundwater or surface water withdrawals in the watershed to normalize results between scenarios.

**Scenario 0B refers to the updated baseline with public drinking water withdrawals estimated from 2018-2022 data. The other scenarios represent the cessation of pumping by town(s) as follows: 1 - Wilmington, 2 – Lynnfield, 3 – Danvers-Middleton, 4 - Topsfield & Ipswich, 5 - Wenham, Hamilton & Ipswich, and 6 – combination of all other scenarios.

1.0 INTRODUCTION

The Horsley Witten–Weston & Sampson team ("the project team") was contracted by the North Shore Water Resilience Task Force (the Task Force) to develop a spreadsheet-based, mass balance model of the Ipswich River watershed ("the model") to support an evaluation of the relative benefits of several planning level water supply alternatives; alternatives were designed to reduce groundwater impacts and increase streamflow and resilience in the Ipswich River watershed. This report summarizes the development of the model and its findings of an evaluation of six proposed water supply alternatives as well as the impact of changes to groundwater withdrawals that have already occurred over the past two decades.

The Ipswich River Watershed includes 22 cities and towns between the river's headwaters in Wilmington and North Andover and its mouth in Ipswich. Water withdrawn from the watershed serves a population significantly greater than the population who actually live in the watershed (at least double by some estimates). According to the Ipswich River Watershed Management Plan (Horsley & Witten, 2003), this imbalance creates an estimated 75-80% net water export from the basin, either as wastewater flow out of basin, or as consumptive water use.



Compounding the significant net export problem, the watershed also has a relatively low percentage of sand and gravel aquifer material, and relatively high rates of stormwater runoff and evapotranspiration, that together limit the amount of water available for aquifer recharge and storage to supply sustained baseflow during extended periods of low precipitation. The baseflow capacity at the sub-basin level can sometimes be significantly less than is the case for the larger watershed.

The Ipswich basin's limited sand and gravel aquifers are situated primarily within river and stream valleys and, as such, the primary locations for large volume groundwater wells have historically been close to streams and rivers. Flow impacts from well withdrawals happen with relatively short lag times due to this physical proximity. Many of these groundwater wells are in sub-basins in the upper parts of the watershed with limited natural recharge capacity such that their negative impacts are proportionally greater, propagating and accumulating through all connected, downstream sub-basins. One metric for understanding the severity of flow issues for many sub-basins within the Ipswich River Watershed is by reference to the state's Sustainable Water Management Initiative (SWMI) wherein all of the basins and sub-basins in the state are categorized by their degree of flow and biological impact for regulatory permitting purposes. As currently categorized by SWMI, seventeen of the 31 sub-basins in the Ipswich Watershed are defined as Groundwater Withdrawal Category (GWC) 4 or 5 (the two most significant flow impact categories) and twelve subbasins are Net Groundwater Depleted in excess of 25%.

In order to evaluate the proposed water supply alternatives against each other from the perspective of improving river flow conditions overall, and for as many sub-basins as possible, the project team developed the Ipswich River Streamflow and Watershed Analysis Model (IRSWAM). IRSWAM is a regional, mass-balance model that provides quantitative support for water suppliers, stakeholders, and decision makers in the watershed. IRSWAM is built upon the methodology of the Water Management Act (WMA) tool, developed by the Massachusetts Department of Environmental Protection (MassDEP) as part of SWMI. SWMI was created under the Massachusetts Executive Office of Energy and Environmental Affairs (EEA) with advisory and technical subcommittees to advise EEA on sustainable water management practices to balance human and ecological needs. SWMI developed a framework to guide MassDEP's permitting process for new water withdrawals under the WMA. The SWMI framework established the Biological Category (BC), Groundwater Withdrawal Criteria (GWC), and other August median flow seasonal criteria – metrics which help define the impacts of water management practices on the environment. SWMI developed a Microsoft Access-based tool (the WMA Tool) to help proponents of potential new withdrawals assess the impacts of their proposed actions against those criteria.

Given that SWMI provides existing quantifiable criteria by which sub-basins can be evaluated, and the fact that SWMI provides a regulatory framework in which water supply is permitted in Massachusetts through the WMA, SWMI metrics, methodologies, and datasets (as incorporated into the WMA Tool) serve as the logical foundation from which IRSWAM was created. Database tables from the WMA Tool were transferred from Microsoft Access for use in the spreadsheet-based IRSWAM. These tables included sub-basin characteristics such as drainage area, septic systems and other groundwater discharges, surface water discharges, public and commercial groundwater withdrawal volumes, private well withdrawal volumes, and unaffected streamflow. IRSWAM also complements the WMA Tool's methodologies in several noteworthy ways. Some of the key features of IRSWAM are:

- Updating the public groundwater withdrawal data underlying the WMA Tool to reflect significant changes that have occurred over the past two decades.
- Providing the ability to add or remove withdrawals in one or more sub-basins simultaneously.
- Allowing new or existing sources to be operated seasonally, not just turning them on or off.
- Harnessing the Response Coefficient method incorporated into the Massachusetts Sustainable Yield Estimator tool (MASYE) v2.0, developed by the United States Geologic Survey (USGS) in cooperation with MassDEP, to account for the time lag between the introduction of new or modified withdrawals and impacts to nearby surface waterbodies.
- Producing model results in the subject sub-basin, but also in all downstream sub-basins.
- Evaluating the impact of proposed changes to groundwater withdrawals or discharges to WMA metrics, such as Flow Alteration and Net Groundwater Depletion and their associated GWCs and Biological Categories (BCs). (See Section 3.6 for precise definitions.)
- Incorporating in-line surface water withdrawals or groundwater discharges.
- Evaluating the impact of surface or groundwater withdrawals and discharges on August median flow conditions throughout the watershed.

As described in this report, IRSWAM was applied by the project team to assess the relative impacts of five alternative water supply scenarios, as well as a sixth combination scenario. These scenarios, provided to the project team by the Task Force, represent the most likely options for reducing water withdrawals within the Ipswich River watershed. These alternatives were assessed using the IRSWAM model, with resultant changes in WMA metrics (i.e. Flow Alteration, Groundwater Withdrawal Category, Net Groundwater Depletion, Biological Category) and other model outputs reported in Section 4.0 below.

Please note that our use of these WMA metrics does not connote any regulatory implications. Rather, the WMA metrics used are a familiar set of criteria with which to evaluate the modeled impacts of different water supply alternatives from a planning perspective. MassDEP has and will continue to rely on the changes to individual subbasin's GWC and BC when evaluating WMA permit applications. In addition, the BC and GWC metrics, as defined under SWMI, are categorical rather than mathematical metrics (i.e., those metrics exist as distinct whole number values between 1 and 5; there is no such thing as a GWC 2.3 for example). Each category represents a range of underlying flow alteration values, so they cannot be truly "averaged". In fact, depending on where within each category's range of flow alteration values fall, averaging could result in skewed conclusions. Watershed-wide averages may also obscure more severe alterations in specific subbasins. However, for the purposes of this IRSWAM modeling project and summary report, BC and GWC subbasin metrics are averaged (using decimal values) across the entire watershed for each scenario in order to characterize the modeled effects of water supply scenarios at a larger scale. Comparing individual subbasin BC and GWC modeled values and changes in watershed-wide average BC and GWC allows for more nuance when comparing water supply scenarios.

2.0 LITERATURE REVIEW

Prior to developing IRSWAM, the project team conducted a literature review of relevant recent studies to document the current water withdrawals landscape and its contribution to streamflow conditions on a seasonal basis with particular attention to low flow periods. That literature review summary memorandum is included herein as Attachment A and is briefly summarized below.

2.1 Documents Reviewed

A growing body of scientific research has been conducted on the symptoms, causes, and potential solutions to the Ipswich River Watershed water budget problem. Studies examined as a part of this literature review are listed below:

- Assessment of Habitat, Fish Communities, and Streamflow Requirements for Habitat Protection, Ipswich River, Massachusetts 1998-1999 (Armstrong et al., 2001);
- A Precipitation-Runoff Model for Analysis of the Effects of Water Withdrawals on Streamflow, Ipswich River Basin, Massachusetts (Zariello and Reis, 2000);
- Ipswich River Watershed Management Plan (Horsley & Witten, January 2003);
- Simulated Effects of the 2003 Permitted Withdrawal and Water-Management Alternatives and Reservoir Storage and Firm Yields in Three Surface-Water Supplies, Ipswich River Basin (Zariello, 2004);
- Effects of Low-Impact-Development Practices on Streamflow, Runoff Quality and Runoff Quantity in the Ipswich River Basin (2010);
- Factors Influencing Riverine Fish Assemblages in Massachusetts (Armstrong et al., 2011);
- Ipswich Basin Water Management Act Planning Grant Study for Fiscal Year (FY) 2017;
- Ipswich Basin Water Management Act Planning Grant Study for FY 2018;
- Drought Management Plan Update, Town of Danvers, Massachusetts, July 2019;
- Below WMA-threshold Study for the Ipswich River and Parker River Basins (MassDEP, 2018 and amended in 2019);
- Minimization Plan, Town of Danvers, Massachusetts, 2019;
- MassDEP Water Management Act (WMA) Program Water Use Data;
- IRWA critique of DEP Below WMA-threshold Study;
- Massachusetts Sustainable-Yield Estimator: A decision-support tool to assess water availability at ungaged stream locations in Massachusetts (SIR 2009-5227, Archfield et al., 2010);
- Methods Used to Estimate Daily Streamflow and Water Availability in the Massachusetts Sustainable-Yield Estimator Version 2.0 (Levin and Granato, 2018);
- Massachusetts Sustainable Water Management Initiative (SWMI) Framework Study (November 28, 2012);
- STRMDEPL08 – An Extended Version of STRMDEPL with Additional Analytical Solutions to Calculate Streamflow Depletion by Nearby Pumping Wells (Reeves, 2008);
- Hydrologic Drought Decisions Support System (HyDroDSS) (Gregory E. Granato, 2014);
- Simulation of Ground-Water Flow and Evaluation of Water-Management Alternatives in the Upper Charles River Basin, Eastern Massachusetts (Leslie A. Desimone, Donald Walter, John Eggleston, and Mark Nimiroski, 2002);

- City of Peabody Integrated Reservoir Model: Coupling Quantity, Conservation; Habitat (Weston & Sampson, 2022);
- MassDEP WMA/SWMI tools and supporting data; and
- 2022 Massachusetts Climate Change Assessment (Executive Office of Energy and Environmental Affairs, December 2022).

2.2 Literature Review Findings

The Ipswich River was designated as one of the most endangered rivers in the United States by the organization American Rivers in 1997 and again in 2021. Segments of the river have experienced extended low flow and dry conditions during summers for at least the last several decades. These low- or no-flow episodes harm riverine fish species and other native biota, hinder recreational opportunities on the river, and threaten water supplies that rely on inflows to refill their reservoirs. The hydrologic challenges facing the Ipswich River Watershed (IRW) have been known and studied for decades and include both natural and anthropogenic contributing factors.

Several natural, physical characteristics of the watershed are thought to contribute to its observed low flow regime, including:

- The relatively shallow nature and limited extent of the sand and gravel aquifers limit the overall groundwater recharge potential and groundwater storage capacity within the watershed. Limited groundwater storage in the watershed limits the capacity to supply sustained baseflow to the river during extended periods of low precipitation.
- The low-lying topography, high groundwater table, and significant area of wetlands favor a relatively high loss of water via evapotranspiration, further limiting the amount of water available for aquifer recharge and storage.

At the sub-basin level, the limitations impacting groundwater recharge and storage due to the physical characteristics described above are often magnified. As a result, the baseflow capacity at the sub-basin level can often be significantly less than is the case for the larger watershed.

The natural watershed characteristics contributing to low flow conditions are compounded by human influences in the watershed associated with the growing population in and around the watershed. The key human factors contributing to low flow include:

- Water withdrawn from the watershed serves a population significantly greater than the population who live in the watershed, creating a situation of significant net water export from the basin. Water delivered to communities with wastewater discharges outside of the watershed represents a significant increase of consumptive water use compared to a scenario without water export. Water used within the basin, when its non-consumptive portion is returned to the aquifer (e.g., septic system effluent), becomes available to contribute baseflow to the river. Water withdrawn from the IRW and discharged out of basin is completely lost.
- This same dynamic of net wastewater export also exists at the sub-basin scale for sub-basins with significant water withdrawals but limited population for wastewater return flow.
- The primary locations for large volume groundwater wells have been historically sited in close proximity to streams and rivers because the Basin's limited sand and gravel aquifers are situated

primarily within river and stream valleys. Due to this proximity, flow impacts from well withdrawals happen with relatively short lag times.

- Many of these groundwater wells are located in sub-basins in the upper parts of the watershed with limited natural recharge capacity such that their impacts are proportionally greater. This can cause greater impacts at the sub-basin scale, which propagate and accumulate downstream to negatively impact all connected, downstream sub-basins.
- Reservoirs in the watershed are both "in-line" and "off-line". Off-line reservoirs in which river water is pumped or otherwise transferred to storage through flood skimming are effective tools for storing excess water harvested during high flow periods and minimizing stream impacts during low flow periods. However, in-line reservoirs that are essentially dammed portions of the river or its tributaries, retain back stream flow at all times of the year and, therefore, withdrawals from these in-line reservoirs represent net losses of available flow to the connected downstream river segments. To the extent that such in-line reservoirs can retain excess water during higher flow periods without decreasing outflow during lower flow periods, they can also provide effective water storage capacity while minimizing downstream flow impacts. Effective management of such in-line reservoirs to provide high flow storage while maintaining low flow throughflow can be complicated from an operational water management perspective.
- Reservoirs are also hydraulically connected to the surrounding aquifer. Higher stages of reservoir storage increase the hydraulic gradient from the reservoir to the aquifer, thereby inducing outward flow from the reservoir to the aquifer which increases aquifer storage and allows for later discharge of that stored groundwater back into the river further downstream. Withdrawals from the reservoir reduce, or even reverse, the gradient from the reservoir to the aquifer and therefore lessen that potential aquifer storage benefit to flow or even induce additional aquifer losses to the reservoir. In addition, higher reservoir stages also have a larger surface area and therefore greater evaporative losses. Reservoir/ aquifer/ flow dynamics are complicated and variable with time, climate, and withdrawals.
- Impervious cover, while modest at the overall watershed scale, is a potentially significant source for lost aquifer recharge in certain sub-basins with a high percentage of effective impervious cover in close proximity to connected stream corridors.

3.0 MODEL DEVELOPMENT

This section describes the development of the Ipswich River Streamflow and Watershed Analysis Model (IRSWAM), beginning with identifying the goals of the model (Section 3.1) and then moving into how those goals informed the framework of the model (Section 3.2) using the WMA Tool as a starting point (Section 3.3). Several key modifications were made to the WMA Tool to meet project goals, beginning with converting the tool to support manipulation of individual wells' withdrawals in multiple sub-basins simultaneously rather than remaining constrained to single source, sub-basin-only inputs (Section 3.4), updating the underlying public groundwater withdrawal data to reflect significant changes that have occurred over the past two decades (Section 3.5), and producing outputs for the subject sub-basin(s) but also all affected downstream sub-basins (Section 3.6). Despite these improvements, the model does have limitations as described in Section 3.7.

3.1 Model Goals

This project builds on previous work completed by the North Shore Water Resilience Task Force member communities, the Ipswich River Watershed Association (IRWA), and others to identify potential solutions that improve streamflow availability in the Ipswich River and reduce the impact of drinking water withdrawals. The specific goal of this project is to develop a model capable of comparing various alternative drinking water supply solutions in a quantitative apples-to-apples manner to understand how and at what scale each solution benefits the watershed and which solutions may do so more effectively or efficiently.

Because any solution would be implemented within the permitting context of the Water Management Act (WMA) and its Sustainable Water Management Initiative (SWMI) framework, IRSWAM was created to evaluate how various solutions might impact key WMA metrics (i.e. Flow Alteration, Groundwater Withdrawal Category, Net Groundwater Depletion, Biological Category), which are described in a bit more detail in Section 3.6.

3.2 Model Framework

The framework of IRSWAM – its input controls, its methodologies and assumptions, and its specific outputs – was developed with those project goals in mind. IRSWAM is a sub-basin scale, mass balance model. It compares typical groundwater withdrawal and discharge rates to an estimate of streamflow, unaffected by withdrawals, impoundments, diversions, or other human influences, on a sub-basin basis. The 31 sub-basins in the Ipswich River watershed are shown in Figure 1.

The 2000-2004 average, sub-basin scale values for private, below WMA threshold groundwater withdrawals and both public and private (septic system) groundwater discharges were obtained from the existing WMA Tool, described in more detail in the following section. Updated groundwater withdrawal values for public and commercial water suppliers, per WMA annual use statistical reports, were incorporated into IRSWAM from data provided to the project team by IRWA in April and May 2024 (see section 3.5 for more detail). These updated withdrawal data reflect significant public water use changes that have occurred in the nearly two decades since the WMA Tool was developed. IRSWAM compares these withdrawals and discharges to estimates of unaffected streamflow, which were calculated using the USGS' (in collaboration with MassDEP) Massachusetts Sustainable-Yield Estimator (MASYE), version 2.0, and incorporated into the existing WMA Tool, where the project team obtained them. This comparison of average groundwater withdrawals and discharges to unaffected August streamflow is at the heart of both the WMA Tool and, consequently, IRSWAM.

IRSWAM can accept user-entered changes to groundwater withdrawals and discharges on a sub-basin scale, but it can also calculate sub-basin scale changes in groundwater withdrawals from the manipulation of specific wells. Described in greater detail in Section 3.4, IRSWAM allows the user to turn wells on or off or change their August average pumping rate up or down by a user-specified amount. IRSWAM also supports the ability to turn wells off or change their pumping rates seasonally, accounting for the lag between a change in pumping and a corresponding change in nearby surface water impacts. IRSWAM calculates how these changes to individual wells affects the default typical groundwater withdrawal rates for one or more of the 31 sub-basins in the Ipswich River watershed and then compares how those sub-basin scale changes impact the WMA metrics (e.g. Net Groundwater Depletion) calculated with 2000-2004 average values. It makes these comparisons not just in the sub-basins where the changes were implemented but in all downstream sub-basins as well to support an understanding of how various scenarios and solutions might provide a trickle-down benefit.

3.3 WMA Tool Conversion

The Massachusetts Department of Environmental Protection's (MassDEP) WMA Tool is a sub-basin scale mass balance model that allows users to evaluate how a change in groundwater withdrawals impacts the WMA metrics in a single sub-basin. Given the overlap of the WMA Tool's uses and outputs with the goals of this project, IRSWAM was developed with the WMA Tool as its foundation. However, the WMA Tool does not currently support:

1. an evaluation of how reductions in drinking water withdrawals will affect waterbodies and sub-basins downstream of the sub-basin in which they occur, or
2. how changes in withdrawal rates and patterns in the spring or other times of year might influence streamflow in August.

To improve on these two limitations, the project team converted the WMA Tool from its current Microsoft Access environment to run in Microsoft Excel, so that improvements could be more readily implemented.

The first limitation is caused by the fact that the databases referenced by the WMA Tool define the Ipswich River watershed's sub-basins on a cumulative basis. The area, unaffected streamflow, and average August groundwater withdrawals and discharges assigned to each sub-basin are the sum of not only the sub-basin itself, but also all upstream sub-basins. To model how changes in one sub-basin propagate downstream, these cumulative databases first had to be disassembled so that IRSWAM could eliminate or change withdrawals and discharges within specific sub-basins. Those immediate or non-cumulative input parameters (inherited from the 2000-2004 data included with the WMA Tool) are shown in Table 3-1 and summarize average August withdrawals and discharges. IRSWAM then adds (or subtracts) changes to withdrawals and discharges back into the affected sub-basin, but also all downstream sub-basins as well. As a result, IRSWAM's output identifies how WMA metrics like Net Groundwater Depletion or GWC might change in downstream communities or river reaches where the WMA Tool cannot. This output is critical for understanding how a 1-MGD reduction in groundwater pumping in one sub-basin, for example, might be better (on a watershed scale) than the same reduction in a different sub-basin.

Table 3-1: Non-Cumulative IRSWAM Sub-Basin Input Parameters For August					
Sub-Basin	Area (mi^2)	Public GW Withdrawals (MGD)	Private GW Withdrawals (MGD)	Public GW Discharges (MGD)	Private GW Discharges (MGD)
21001	0.35	0.000	0.002	0.000	0.007
21002	2.09	0.045	0.006	0.000	0.041
21003	1.82	0.249	0.009	0.000	0.041
21004	2.77	0.931	0.002	0.000	0.096
21005	2.98	0.000	0.014	0.009	0.101
21006	4.49	0.001	0.010	0.000	0.084
21007	3.43	0.073	0.006	0.000	0.030
21008	2.33	0.003	0.018	0.000	0.039
21009	2.01	0.291	0.053	0.000	0.074
21012	4.52	0.000	0.006	0.000	0.110
21013	8.59	0.650	0.030	0.000	0.370
21018	3.41	0.000	0.026	0.000	0.096
21019	3.30	0.232	0.066	0.043	0.096
21020	5.04	0.000	0.050	0.000	0.101
21021	0.96	0.000	0.015	0.000	0.027
21031	3.21	0.196	0.004	0.000	0.029
21032	7.61	0.000	0.012	0.000	0.133
21041	10.24	0.000	0.117	0.000	0.256
21065	5.74	0.008	0.144	0.000	0.127
21066	1.80	0.008	0.002	0.000	0.014
21067	3.15	0.000	0.006	0.000	0.072
21068	6.31	0.110	0.021	0.039	0.179
21069	2.73	0.000	0.038	0.000	0.045
21070	7.88	0.010	0.201	0.000	0.168
21071	5.36	0.000	0.058	0.000	0.084
21072	8.29	0.000	0.074	0.000	0.202
21073	13.22	2.585	0.037	0.077	0.491
21074	9.45	2.371	-0.010	0.005	0.313
21076	5.89	0.401	0.034	0.000	0.474
21077	8.54	0.808	0.046	0.000	0.408
21217	2.51	0.000	0.003	0.000	0.017

The second limitation of the WMA Tool with regard to meeting this project's goals, is its inability to dynamically represent the lag between eliminating or changing groundwater pumping rates and a corresponding change in nearby streamflow availability. The project team's elimination of this limitation in IRSWAM is described in detail in the following section but was facilitated by the conversion of the WMA Tool from Access to Excel.

3.4 Individual Source Manipulation

Studies of groundwater-surface water interactions throughout Massachusetts and neighboring states (Reeves, 2008 and Granato, 2014) indicate that the lag between a change in groundwater pumping and the full impact on nearby surface waterbodies can be on the order of weeks or even months in watersheds like the Ipswich. In order to capture this lag effect, the project team incorporated the Response Coefficient methodology into IRSWAM, the same methodology that the USGS incorporated into the MASYE, version 2.0. The Response Coefficient method calculates the fraction of a change in groundwater pumping (or discharge) that is translated to changes in baseflow as a function of the number of months elapsed, distance, and aquifer diffusivity over that intervening distance.

The project team created a sub-routine in IRSWAM that allows the user to identify the magnitude and timing (i.e. start month) of changes at individual wells in the watershed. IRSWAM then applies the Response Coefficient method to estimate what fraction of those changes will be experienced at the nearest USGS-mapped shoreline or stream centerline in August. In the case of the six alternatives discussed in Section 4, those fractions typically range from 90 to 94%. IRSWAM then applies those fractional changes in pumping rate at individual wells to the sub-basin they are located within, allowing the user to:

- manipulate multiple wells in the same or in different sub-basins,
- turn some wells on/off while increasing or decreasing the withdrawal rate at others,
- and even implement these changes in different months.

Alternatively, IRSWAM also allows the user to turn this Response Coefficient functionality off and assume that any changes in groundwater well pumping rates is experienced at a 1:1 ratio by nearby surface waterbodies. This enhanced Response Coefficient approach was considered with regard to evaluating the water supply alternatives in this study but ultimately not employed as discussed in Section 4.2.1. In the SWMI studies and therefore in the WMA tool, a 1:1 ratio is assumed.

3.5 Updated Withdrawal Data

In addition to addressing several limitations of the WMA Tool to achieving this project's goals, the project team also incorporated updated public and commercial groundwater withdrawal data (regulated by the WMA) used to help drive IRSWAM, reflecting the discontinuation of several supply sources and a change to the August average pumping rates of other sources over the nearly two decades since the original WMA Tool was first developed. Updated public and commercial groundwater withdrawal rates were provided to the project team by IRWA via email correspondence with Ryan O'Donnell on May 1, 2024, for each active – used here to indicate regular use rather than the regulatory designation – groundwater source. Those sources and their associated August average pumping rates for the period 2018-2022 are summarized in Table 3-2.

Table 3-2: IRSWAM Public & Commercial Groundwater Withdrawal Points					
PWS Point ID	**Withdrawal Point**	**Sub-Basin**	**System Name**	**August Avg. Withdrawal (MGD)**	**2024 Study Scenario**
PWS-3298000-02G	PERKINS ROW TUB WELL	21003	Topsfield	0.161	4
PWS-3119000-05G	IDLEWOOD #1 WELLS	21004	Hamilton	0.288	5
PWS-3119000-06G	IDLEWOOD #2 G.P. WELL	21004	Hamilton	0.054	5
PWS-3119000-07G	PLATEAU G.P. WELL	21004	Hamilton	0.144	5
PWS-3119000-08G	SATELLITE	21004	Hamilton	0.104	5
PWS-3320000-01G	GP WELL # 1	21004	Wenham	0.269	5
PWS-3320000-02G	GP WELL # 2	21004	Wenham	0.114	5
PWS-3144000-04G	WINTHROP GD WELL # 2	21007	Ipswich	0.089	4, 5
PWS-3298000-01G	NORTH ST. TUB WELL	21009	Topsfield	0.316	4
PWS-3164000-02G	MAIN STREET G.P. WELL	21013	Lynnfield	0.153	2
PWS-3164000-05G	GLEN DRIVE WELL #1	21013	Lynnfield	0.134	2
PWS-3164000-06G	GLEN DRIVE WELL #2	21013	Lynnfield	0.069	2
PWS-3164000-07G	GLEN DRIVE WELL #3	21013	Lynnfield	0.067	2
PWS-3164000-08G	GLEN DRIVE WELL #4	21013	Lynnfield	0.038	2
PWS-WM3837-01G	SUTLIFF WELL	21013	Thomson CC	0.065	---
PWS-3071000-02G	WELL # 2	21019	Danvers	0.076	3
PWS-3144000-06G	ESSEX RD GP & GD WELLS	21031	Ipswich	0.071	4, 5
PWS-3144000-07G	FELLOWS RD. G.D. WELL	21031	Ipswich	0.087	4, 5
PWS-3119000-02G	SCHOOL G.P. WELL	21068	Hamilton	0.045	5
PWS-3342000-11G	BROWNS CROSSING REPLACEMENT WELLFIELD	21073	Wilmington	0.695	1
PWS-3342000-12G	BARROWS REPLACEMENT WELLFIELD	21073	Wilmington	0.285	1
PWS-3342000-13G	SALEM ST. WELL	21073	Wilmington	0.000	1
PWS-3342000-14G	SALEM ST. REPLACEMENT WELLFIELD	21073	Wilmington	0.401	1
PWS-3342000-05G	SHAWSHEEN AVE. GP WELL	21076	Wilmington	0.456	1
PWS-3342000-06G	ALDRICH RD. GP WELL	21076	Wilmington	0.000	1

We note that while public groundwater withdrawal data was updated in IRSWAM from its original WMA Tool values, public groundwater discharge and private groundwater withdrawal and discharge values on a sub-basin scale were not updated as those updated data were not available. These rates have likely increased with population growth, but to what degree or how that growth is spatially distributed throughout the watershed's 31 sub-basins is unknown. While MassDEP's 2018 Below WMA-threshold Study and IRWA's 2019 critique of that study (Refer to Section 2 Literature Review) discuss private well withdrawals at the watershed scale, such private withdrawal data is not available at the sub-basin scale and, therefore, not usable for this modeling project. This represents a limitation to the model, which may particularly impact conclusions for those sub-basins with significant private withdrawals and/or changes to those private withdrawals in the last two decades. According to the MassDEP Below WMA Threshold Study (MassDEP, 2018), WMA-regulated withdrawals represent approximately 95% of the total annual withdrawals within the Ipswich Basin.

It should be noted that in its' 2019 critique of the 2018 MassDEP study IRWA states that the volume of below threshold withdrawals was at least double that reported by MassDEP and that the impact of those below threshold withdrawals was even greater due to the likely seasonality of irrigation withdrawals during the low flow summer season. According to the Task Force, more recent discussions between DEP, IRWA, and other Task Force members have coalesced to agreement that below threshold withdrawals are likely significantly greater than the 5% value indicated in the 2018 DEP report. No updated report has been released by DEP as of the writing of this report. Please refer to Section 2 and Appendix A of this report for more details on the MassDEP study and the IRWA critique. We note, that beyond the question of total magnitude and significance of below threshold withdrawals on the watershed scale, there could potentially be significant impacts at the sub-basin scale if there were significant concentrations of these below threshold withdrawals in specific sub-basins. To our knowledge, there is currently no reliably quantifiable estimate of below threshold withdrawals on the sub- basin scale.

3.6 Model Outputs

Given that one of the goals of this study is to understand how several theoretical water supply alternatives might affect flow availability in the Ipswich River watershed through the lens of the WMA regulatory framework, IRSWAM inherits several model outputs inherited from the WMA Tool from which it was initially developed. Those "WMA metrics," which are all calculated on a cumulative sub-basin basis (including all upstream sub-basins) are defined as:

- Flow Alteration – The ratio of August groundwater pumping to unaffected streamflow (August median unaffected flow per the SYE2 Tool)
- Groundwater Withdrawal Category (GWC) – Based on Flow Alteration
    - GWC1: 0 to 3% altered
    - GWC2: 3 to 10% altered
    - GWC3: 10 to 25% altered
    - GWC4: 25 to 55% altered
    - GWC5: >55% altered
- Net Groundwater Depletion – The ratio of the sum of August groundwater pumping and discharges to unaffected streamflow (August median unaffected flow per the SYE2 Tool)
- Biological Category (BC) – Based on Flow Alteration
    - BC1: 0 to 5% depleted
    - BC2: 5 to 15% depleted
    - BC3: 15 to 35% depleted
    - BC4: 35 to 65% depleted
    - BC5: >65% depleted

    The Biological Category within the Massachusetts Sustainable Water Management Initiative (SWMI) Framework assesses the health of a sub-basin by evaluating its aquatic habitat, particularly fish populations. The BC of a sub-basin is determined through a regression equation that incorporates several environmental variables. The precise formula used to calculate the BC is detailed in the SWMI Technical Resources. The key variables considered in the regression equation include: Flow Alteration, impervious cover percentage, wetlands cover percentage, and average stream channel slope. In evaluating various water supply alternatives, we have assumed that only groundwater withdrawals are modified – potentially modifying a sub-basin's or sub-basins' Flow Alteration – but that impervious cover percentage, wetlands cover percentage, and stream channel slope would remain unchanged.

In addition to the four WMA metrics identified above, which were designed by the creators of the WMA Tool to evaluate the impacts of changes to groundwater withdrawals and discharges, IRSWAM includes an additional output to provide greater context to the potential streamflow benefits of various water supply alternatives, including their proposed changes to surface water withdrawals or discharges:

- *August Median Affected Flow*. IRSWAM calculates and outputs an August Median Affected Flow on a sub-basin basis, by first calculating the net change of all groundwater and surface water fluxes in the watershed and then subtracting that total net flux from an estimate of the August median unaffected flow, derived from the SYE2 Tool, and used by the WMA Tool, in part, to calculate Flow Alteration and Net Groundwater Depletion.

3.7 Model Limitations

IRSWAM draws on the best available data and analytical tools to assess the relative impact of various water withdrawal scenarios within the Ipswich River Watershed. The tools combined within IRSWAM are the very tools utilized to develop the SWMI framework and used in the WMA permitting process and, therefore, IRSWAM inherits both the benefits and inherent accuracy limitations of those tools. While IRSWAM is a powerful tool with which to evaluate the potential benefits of water supply alternatives on August flow availability in the Ipswich River Watershed, it does have limitations, rooted in its framework and in the datasets that drive the model, many of which are inherited from the WMA Tool and MASYE 2.0 models developed by others. These limitations should be considered when interpreting any results produced by the model.

The WMA tool is a Microsoft Access database and serves as the primary data source for IRSWAM. The WMA tool combines several datasets to calculate outputs for estimated August flow volumes, including the Groundwater Withdrawal and Biological Category. Unaffected streamflow, a component of these calculations, is derived from the Massachusetts Sustainable Yield Estimator (MASYE), which presents the first potential source of error incorporated in IRSWAM. MASYE is a statistical model developed to estimate hydrography for ungauged streams. The model regresses flow duration curves (FDC) based on 17 exceedance probabilities from gauged streams to estimate those same flow conditions for ungauged streams. Six of these exceedance probabilities are based on physical characteristics of the ungauged basin, including drainage area, basin elevation, precipitation, percentages of open water wetlands and sand and gravel deposits, average maximum monthly temperature, location of the basin outlet and centroid, and a correction factor. Intermediate flow and low flow probabilities are calculated by explanatory variables regressed from streamflow quantiles. The flow duration curves calculated from these statistical relationships are translated into time series data using the QPPQ method and a map-correlated reference gauge. The QPPQ method, originally developed by Fennessey (1994) and adopted by many others, relates long-term streamflow measurements at a gauged location to estimated daily flows at an ungauged location by the incorporation of analysis of exceedance probabilities and physical-characteristic relationships between the reference and ungauged target watersheds. The flow data incorporated in these statistical relationships spans water years 1961 through 2004.

Uncertainty in estimated unaltered streamflow from the MASYE is grouped into two major buckets – uncertainty in the regression equations and interpolation of the FDC, and uncertainty in selecting the appropriate reference gauge. Total uncertainty for median or monthly median unaltered streamflow records is assessed in the MASYE technical report with an error range of ±20%. The incorporation of MASYE estimated flows in the WMA permitting tool makes the values an appropriate basis for inclusion in IRSWAM. The estimates the MASYE provides represent long-term average yearly conditions and do not account for yearly variability in conditions. These conditions represent those expected during the period of data and do not account for changes in precipitation due to climate change since the period of record for reference streams (1961-2004) or anticipated future conditions. Additionally, the outputs of MASYE captured at the time those results were incorporated in the WMA tool reflect the basin physical characteristics at that time and do not reflect any changes in those characteristics since that time.

The WMA tool also incorporates water withdrawal data from water use points throughout the Ipswich River watershed. Public water use data was updated by IRWA using data reported to MassDEP on the Annual Statistical Reports during the development of IRSWAM as one means of reducing potential error within the model from what was inherited through the WMA tool database. Water use values for 36 water systems in the Ipswich River basin incorporated in the WMA tool database are based on data from 2000-2004. Updated values for 30 systems were provided by IRWA to update baseline water use in IRSWAM reflecting the years 2018 to 2022, providing a significant improvement to the currency of the model. While public groundwater withdrawals have been updated to reflect conditions present in 2018-2022, data were not available to similarly update public discharges and private groundwater withdrawals and discharges. Those data continue to represent 2000-2004 conditions as in the original WMA Tool.

Additional IRSWAM limitations include the following:

- IRSWAM is a mass-balance model. It is designed to evaluate the relative, not absolute, impacts associated with changes in groundwater withdrawals or discharges, and to a lesser degree, changes in surface water withdrawals and discharges.
- As a mass-balance model, IRSWAM inputs and outputs represent a single, typical set of average conditions. It would not be appropriate to use the model to attempt to recreate a particular moment in time or to use it to evaluate transient conditions.
- IRSWAM is designed to calculate relative impacts of proposed changes to withdrawals and discharges at the sub-basin scale. The user is cautioned against manipulating IRSWAM's input variables in order to reflect hydrologic or hydraulic processes on a smaller scale or extending its outputs to a smaller scale.
- Like the WMA Tool, IRSWAM is designed to evaluate changes in groundwater withdrawals and discharges. IRSWAM also supports the ability to evaluate changes to surface water withdrawals and discharges within a sub-basin, but most WMA metrics, with their regulatory implications, are not applicable to or affected by changes in surface water fluxes.
- Most WMA Tool and, consequently, IRSWAM outputs reference August Median Unaffected Streamflow as determined from the SYE2 Tool. We note that those unaffected flow regimes have likely been influenced by and will continue to be influenced by climate change.
- Uncertainty analysis has not been conducted on model results. Uncertainty may be large given the uncertainty in the input data. However, large relative improvements among scenarios for ranking purposes are likely appropriate.

Despite these limitations, IRSWAM, like the WMA Tool it is derived from, is a useful tool for evaluating the relative impacts and effectiveness of various public drinking water supply alternatives. It is important to note that the intention of IRSWAM is not to provide a physical model of numerically accurate flows in the Ipswich basin, but rather to assess the relative impact of water withdrawal changes between select alternatives. The decision to utilize the WMA tool and the MASYE estimates included therein stems from the effectiveness of those tools and datasets towards the main purpose of IRSWAM for evaluating the relative efficacy of water supply alternatives within the regulatory framework of the WMA provided by SWMI. IRSWAM's use of those tools and datasets also has the advantage of expanding upon a familiar and well-understood representation of water mass balance with relative simplicity. The data sources incorporated represent the best available estimate of the physical drivers of streamflow in addition to being the datasets utilized to develop the SWMI framework and WMA permitting process, updated to reflect more recent conditions.

Please note that our use of these WMA metrics does not connote any regulatory implications. Rather, the WMA metrics used are a familiar set of criteria with which to evaluate the modeled impacts of different water supply alternatives from a planning perspective. MassDEP has and will continue to rely on the changes to individual subbasin's GWC and BC when evaluating WMA permit applications. In addition, the BC and GWC metrics, as defined under SWMI, are categorical rather than mathematical metrics (i.e., those metrics exist as distinct whole number values between 1 and 5; there is no such thing as a GWC 2.3 for example). Each category represents a range of underlying flow alteration values, so they cannot be truly "averaged". In fact, depending on where within each category's range of flow alteration values fall, averaging could result in skewed conclusions. Watershed-wide averages may also obscure more severe alterations in specific subbasins. However, for the purposes of this IRSWAM modeling project and summary report, BC and GWC subbasin metrics are averaged (using decimal values) across the entire watershed for each scenario in order to characterize the modeled effects of water supply scenarios at a larger scale. Comparing individual subbasin BC and GWC modeled values and changes in watershed-wide average BC and GWC allows for more nuance when comparing water supply scenarios.

4.0 WATER SUPPLY ALTERNATIVES EVALUATION

This section first summarizes the impacts of updating the public and commercial groundwater withdrawal data from their original values, as described in Section 3.5, on WMA metrics and other IRSWAM outputs. As discussed in Section 4.1, updating those values to reflect approximately two decades of changes to drinking water withdrawals in the Ipswich River watershed has led to significant modeled impacts. This section then goes on to define and evaluate six theoretical water supply alternatives with Section 4.2 summarizing what those alternatives are and how they were modeled. Sections 4.3 and 4.4 document the changes in WMA metrics and other IRSWAM outputs associated with those alternatives, at the watershed and sub-basin scale, respectively. Key findings are summarized in Section 4.5.

4.1 Impact of Updating Withdrawal Data

As noted in Section 3.5, the IRSWAM was developed initially with sub-basin scale mass balance inputs as incorporated into the WMA Tool, including 8.972 MG of public or commercial groundwater withdrawals, as estimated by MassDEP from public water supply withdrawal data gathered between 2000 and 2004. During model development, those incorporated groundwater withdrawals were replaced by estimates of August average withdrawals between 2018 and 2022, as tabulated and provided to the project team by IRWA. The new watershed-wide total of public groundwater withdrawals, 4.217 MGD, is 4.755 MGD lower that the original WMA Tool values, a 53% reduction.

The watershed-wide WMA metrics and other IRSWAM outputs comparing the original withdrawals (Scenario 0A) to more recent withdrawals (Scenario 0B) suggest these reductions have resulted in a significant improvement in the modeled streamflows. Under Scenario 0A, the watershed-wide average Flow Alteration was 54% while the Net Groundwater Depletion was 29%. The reduction in public drinking water withdrawals over the past 20 years resulted in a 26% decrease in both Flow Alteration and Net Groundwater Depletion, reducing them to 28 and 3%, respectively. As a result, the average GWC has decreased as well, from 3.40 to 2.82, while BC remained unchanged. It should be noted that GWC and BC are whole number quantities applicable to individual sub-basins within the WMA Tool and WMA regulations. Additional decimal places for these metrics are used herein to reflect averaging across all of the sub-basins and better allow for an appreciation of the overall magnitude of modeled potential changes.

Table 4-1: IRSWAM Outputs for Original vs. Updated GW Withdrawals

Scenario	Description	Flow Alteration	GWC	Net GW Depletion	BC	August Median Affected Flow (cfsm)
0A	Original WMA Tool (2000-2004)	54%	3.40	29%	4.48	0.147
0B	Updated Withdrawals (2018-2022)	28%	2.82	3%	4.48	0.182
	Change	-26%	-0.58	-26%	-0.00	0.035
	% Change	-48%	-17%	-90%	-0%	19%

It is important to note here that, as called out previously in this report, the WMA Tool and IRSWAM are limited in large part by the available WMA withdrawal and discharge data. There is a question of to what extent the public drinking water withdrawal reductions indicated above may be offset by shifts to private well use and reservoir withdrawals that are not captured by the available WMA data behind the WMA Tool and IRSWAM. In this context, the project team is aware of the findings of preliminary analyses of USGS flow data conducted by the Massachusetts Department of Conversation and Recreation (MassDCR). Those analyses compared flow regimes in the upper and lower Ipswich River watersheds against reference gages in nearby watersheds, both before and after the significant changes in public drinking water withdrawals in the Ipswich over the past two decades. Those preliminary findings indicated that while more moderate flow regimes (e.g. 20th percentile flows) increased throughout the Ipswich River watershed when compared to reference gages, the lower half the Ipswich watershed did not experience as significant an increase as the upper half. Furthermore, lower flow regimes (e.g. 2nd and 10th percentile flows) were actually shown to decrease or worsen in the lower half of the Ipswich River watershed when compared to reference gages, whereas the upper Ipswich experienced increases in those lower flow regimes.

These differences in upper and lower watershed low flow metrics may be explained by the fact that many of the largest reductions in groundwater withdrawals over the past 20 years were located in the upper half of the watershed. The benefits to streamflow would naturally appear strongest there. Those benefits would tend to be watered down, further downstream in the lower reaches of the Ipswich. In addition, as reported by some Task Force members, there may be an increasing use of private wells in the lower watershed that is not captured by WMA data or IRSWAM.

Acknowledging these important nuances with regard to watershed scale changes over the past 20 years, the model showed significant changes on a sub-basin scale as well. Table 4-2 presents the sub-basin scale changes to Flow Alteration and the associated GWC. As highlighted in light blue, 11 of the 31 sub-basins in the watershed were modeled to have such significant improvements to Flow Alteration that their GWCs would be lowered, generally from 5s and 4s to 4s or 3s, although in the case of sub-basin 21077, its GWC dropped from a 4 to a 1. Sub-basin scale changes in GWC can be seen visually by comparing Figures 2A and 2B, which present the GWC for each sub-basin with the original WMA withdrawal rates and the updated IRSWAM withdrawal rates, respectively. Figures 3A and 3B provide a similar comparison for sub-basins' modeled Flow Alteration.

Modeled improvements to Net Groundwater Depletion were also significant although in no case did a sub-basin's calculated BC change, as shown in Table 4-3. Sub-basin scale modeled changes in Net Groundwater Depletion can be seen visually by comparing Figures 4A and 4B, which present the Net Groundwater Depletion for each sub-basin with the original WMA withdrawal rates and the updated IRSWAM withdrawal rates, respectively. August Median Affected Flows were also modeled to have significantly improved in most sub-basins throughout the watershed as a result of reductions to public drinking water withdrawals over the past two decades. As shown in Table 4-4, below, changes in modeled August Median Affected Flows range from a decrease of 0.110 cfsm to an increase of 0.202 cfsm. Note again that these modeled improvements may be offset by shifts to private well use and reservoir withdrawals that are not captured by the available WMA data behind the WMA Tool and IRSWAM, as suggested by MassDCR's flow analysis, described above.

Table 4-2: Comparison of Flow Alteration and GWC on a Sub-Basin Scale (Scenario 0A vs. Scenario 0B)*

Sub-Basin ID	Flow Alteration		GWC	
	Scenario 0A	Scenario 0B	Scenario 0A	Scenario 0B
21001	36%	37%	4	4
21002	50%	26%	4	4
21003	121%	80%	5	5
21004	278%	291%	5	5
21005	51%	21%	4	3
21006	2%	2%	1	1
21007	48%	25%	4	3
21008	7%	6%	2	2
21009	47%	49%	4	4
21012	1%	1%	1	1
21013	100%	36%	5	4
21018	7%	7%	2	2
21019	88%	32%	5	4
21020	12%	12%	3	3
21021	82%	30%	5	4
21031	13%	9%	3	2
21032	1%	1%	1	1
21041	11%	11%	3	3
21065	20%	19%	3	3
21066	47%	24%	4	3
21067	1%	1%	1	1
21068	7%	4%	2	2
21069	10%	10%	3	3
21070	14%	14%	3	3
21071	62%	24%	5	3
21072	9%	9%	2	2
21073	143%	77%	5	5
21074	117%	17%	5	3
21076	187%	78%	5	5
21077	48%	3%	4	1
21217	41%	22%	4	3
Watershed-Wide Weighted Average	**54%**	**28%**	**3.40**	**2.82**

**Scenario 0A is defined with original WMA Tool withdrawals from 2000-2004. Scenario 0B is defined with 2018-2022 withdrawal data provided by IRWA.*

Table 4-3: Comparison of Net Groundwater Depletion and BC on a Sub-Basin Scale (Scenario 0A vs. Scenario 0B)*

Sub-Basin ID	Net GW Depletion		BC	
	Scenario 0A	Scenario 0B	Scenario 0A	Scenario 0B
21001	19%	20%	5	5
21002	29%	5%	5	5
21003	102%	60%	5	5
21004	249%	262%	5	5
21005	28%	-1%	5	5
21006	-14%	-14%	3	3
21007	29%	6%	5	5
21008	-6%	-7%	4	4
21009	28%	30%	5	5
21012	-17%	-17%	5	5
21013	70%	5%	5	5
21018	-20%	-20%	4	4
21019	59%	4%	5	5
21020	-12%	-12%	4	4
21021	54%	2%	5	5
21031	-1%	-5%	4	4
21032	-11%	-11%	4	4
21041	-13%	-13%	4	4
21065	3%	2%	4	4
21066	27%	5%	5	5
21067	-16%	-16%	3	3
21068	-10%	-13%	4	4
21069	-12%	-12%	4	4
21070	-4%	-5%	4	4
21071	38%	0%	5	5
21072	-15%	-15%	4	4
21073	112%	46%	5	5
21074	79%	-22%	5	5
21076	118%	9%	5	5
21077	25%	-20%	5	5
21217	23%	3%	5	5
Watershed-Wide Weighted Average	**29%**	**3%**	**4.48**	**4.48**

**Scenario 0A is defined with original WMA Tool withdrawals from 2000-2004. Scenario 0B is defined with 2018-2022 withdrawal data provided by IRWA.*

Table 4-4: Comparison of August Median Affected Flows on a Sub-Basin Scale (Scenario 0A vs. Scenario 0B)*			
Sub-Basin ID	**August Median Affected Flows (cfsm)**		
	Scenario 0A	**Scenario 0B**	**Change**
21001	0.174	0.172	-0.002
21002	0.172	0.224	+0.053
21003	-0.003	0.072	+0.075
21004	-0.281	-0.304	-0.023
21005	0.170	0.232	+0.063
21006	0.202	0.203	0.000
21007	0.173	0.223	+0.051
21008	0.202	0.204	+0.002
21009	0.150	0.147	-0.003
21012	0.246	0.246	0.000
21013	0.071	0.222	+0.151
21018	0.191	0.081	-0.110**
21019	0.098	0.231	+0.132
21020	0.147	0.062	-0.085**
21021	0.111	0.227	+0.116
21031	0.239	0.220	-0.018
21032	0.247	0.185	-0.062**
21041	0.180	0.180	0.000
21065	0.197	0.199	+0.002
21066	0.180	0.229	+0.049
21067	0.234	0.234	0.000
21068	0.255	0.229	-0.027
21069	0.171	0.171	0.000
21070	0.202	0.202	+0.001
21071	0.147	0.226	+0.079
21072	0.178	0.178	0.000
21073	-0.026	0.115	+0.141
21074	0.043	0.245	+0.202
21076	0.191	0.177	-0.015
21077	0.144	0.231	+0.087
21217	0.196	0.236	+0.041
Watershed-Wide Weighted Average	**0.147**	**0.182**	**0.035**

**Scenario 0A is defined with 2000-2004 WMA Tool withdrawals. Scenario 0B is defined with 2018-2022 withdrawals from IRWA.*

***These sub-basins' surface water withdrawals were modified under Scenario 0B. See Section 4.2.2 for a detailed discussion.*

Note that three sub-basins (21018, 21020, and 21032) were modeled to have particularly significant reductions in August Median Affected Flow. This is caused by those three sub-basins' updated baseline

(Scenario 0B) being adjusted to represent in-line reservoir operations in those sub-basins, which were not incorporated into the original baseline (Scenario 0A). As discussed in Section 3.7 regarding model limitations, the WMA Tool, and therefore IRSWAM were not developed to specifically assess surface water changes. The project team was instructed by the Task Force to represent the August water budget implications of the use of three in-line reservoirs within these sub-basins by subtracting out an estimate of natural flow at their respective outlets using the Sustainable Yield Estimator (SYE) tool v2.0, assuming zero flow over these dams in August. Detail regarding the value of those streamflow adjustments, the waterbodies in question, and their associated drainage areas and sub-basin IDs is provided in Table 4-5:

Table 4-5: Surface Water Reservoir Modifications Incorporated into Scenario 3

Waterbody	Drainage Area (mi^2)	MASYE2.0 August Median Unaffected Flow (MGD / cfs)	Sub-Basin
Wenham Lake	2.16	0.304 / 0.47	21032
Middleton Pond	2.79	0.243 / 0.38	21018
Emerson Brook Reservoirs	3.46	0.278 / 0.43	21020

Two of the water supply alternative scenarios (described in Section 4.2 below) were defined by the Task Force to include elimination of the surface water withdrawals in sub-basins 21018 and 21020. For these two alternatives, the subtracted SYE-estimated flows at the outlets of these reservoirs were then added back in, representing the surface water impoundments becoming run-of-river dams, as discussed below in Section 4.2.2.

While IRSWAM results and MassDCR's analyses suggest significant heterogeneity with regard to changes in Ipswich River streamflow regimes as a result of changes in public drinking water withdrawals over the past two decades, when averaged across all sub-basins in the watershed and weighted based on their respective drainage areas, modeled August Median Affected Flows have increased. In fact, IRSWAM results suggest that the watershed-wide average increase in August Median Affected Flow from Scenario 0A to 0B is approximately 0.035 cfsm (or 19%).

It is important to note that all of the modeled watershed improvements noted above, produced by reductions in public groundwater withdrawals over the past two decades, are likely to be somewhat overstated. The large reduction in public drinking water withdrawals in the watershed does not appear to have been caused by a similarly large reduction in demand, but rather they may have been caused in part by a shift to alternative sources of supply located outside the watershed and also by a switch to private groundwater withdrawals within the watershed. While updates made to IRSWAM to reflect changes in public drinking water withdrawals over the past two decades reflect the former, no corresponding increases were made to private drinking water withdrawal inputs due to a lack of available data. This limitation is likely to produce an overstating of improvements to the watershed's streamflow regime over the past two decades, as underscored by the MassDCR analysis described above.

4.2 Overview of Alternatives

Six planning level water supply alternatives were identified by the Task Force and provided to the project team for evaluation with IRSWAM. All six alternatives or scenarios included the cessation of pumping at one or more public groundwater wells in the month of May. The definitions of each of those six alternatives, including the specific groundwater supply wells that were "turned off" and the associated water suppliers, are identified in Table 4-6. Additional details regarding those proposed changes are discussed in Section 4.2.1.

Two of the Task Force recommended scenarios also included the elimination of surface water reservoir withdrawals. MassDEP's original WMA Tool, from which IRSWAM is derived both conceptually and as implemented, does not directly support the evaluation of changes to surface water withdrawals. As such, use of IRSWAM to evaluate changes in surface water reservoir withdrawals requires conceptualization of those surface water withdrawal changes as equivalent groundwater withdrawals. The Task Force and the project team have differing opinions about how best to accomplish that conceptualization. The Task Force's requested methodology for that conceptualization, used in this modeling effort to evaluate the potential benefits of eliminating some surface water withdrawals, is described in Section 4.2.2.

Table 4-6: Water Supply Alternatives

Scenario	Supplier(s)	Sources Affected	Combined Withdrawals (MGD)
1	Wilmington	PWS-3342000-11G, PWS-3342000-12G, PWS-3342000-13G, PWS-3342000-14G, PWS-3342000-05G, PWS-3342000-06G	1.837
2	Lynnfield	PWS-3164000-02G, PWS-3164000-05G, PWS-3164000-06G, PWS-3164000-07G, PWS-3164000-08G	0.461
3	Danvers-Middleton	PWS-3071000-02G (plus Middleton Pond and Emerson Brook Reservoir)	0.597
4	Topsfield & Ipswich	PWS-3298000-02G, PWS-3144000-04G, PWS-3298000-01G, PWS-3144000-06G, PWS-3144000-07G	0.724
5	Wenham, Hamilton & Ipswich	PWS-3119000-05G, PWS-3119000-06G, PWS-3119000-07G, PWS-3119000-08G, PWS-3320000-01G, PWS-3320000-02G, PWS-3144000-04G, PWS-3144000-07G, PWS-3119000-02G, PWS-3342000-02G	1.265
6	Combined 1, 2, 3, 4, and 5	All of the above	4.637

4.2.1 Groundwater Withdrawals

As discussed in Section 3.4, the elimination of pumping from a well in May does not necessarily translate to a 1:1 increase in nearby streamflow availability in August. IRSWAM was developed to evaluate the reduced effectiveness of these six water supply scenarios with and without accounting for that lag. Table 4-7 identifies the deviation between a scenario's total reduction in pumping (under a 1:1 assumption) and its associated increase in streamflow when accounting for that lag. As shown in the table, those deviations range between 1 and 10% with all but Scenario 3 ranging between 6 and 10%. Given the relatively small magnitude of those deviations, the remaining tables, maps, and text of this report will focus on those variations of each scenario that assume a 1:1 ratio and do not include that lag effect and its associated reduction in the effectiveness of eliminating groundwater pumping on a seasonal basis.

Table 4-7: Watershed-Wide Reduction in August Groundwater Withdrawals by Scenario, With and Without Accounting for a Lag in Streamflow Response

Scenario	Supplier(s)	Reduction (MGD)	Reduction with Lag (MGD)	Deviation (MGD)	Deviation (%)
1	Wilmington	1.837	1.664	0.173	9%
2	Lynnfield	0.461	0.413	0.048	10%
3	Danvers-Middleton	0.901	0.895	0.006	1%
4	Topsfield & Ipswich	0.724	0.682	0.042	6%
5	Wenham, Hamilton & Ipswich	1.265	1.143	0.122	10%
6	Combined 1, 2, 3, 4, and 5	4.941	4.574	0.367	7%

4.2.2 Surface Water Modifications

Scenario 3, and consequently Scenario 6, were defined by the Task Force to include, in part, the cessation of the Danvers Water Department's surface water withdrawals from Middleton Pond and Emerson Brook Reservoirs. As discussed in Section 3.7 regarding model limitations, the WMA Tool was not designed to evaluate the impact of changes to surface water withdrawals. While IRSWAM was designed to allow the manipulation of surface water withdrawals and discharges and to evaluate the impact of those changes on August Median Affected Flow, the mass balance methodology incorporated into both the WMA Tool and IRSWAM was not necessarily developed with surface water changes in mind. Care must be taken in conceptualizing changes to surface water fluxes at a single point in time. The Task Force requested that the evaluation of Scenario 3 assume that the "downstream impact of ceasing the use of the two reservoirs in question is equal to the equivalent natural flow at these points (i.e. the SYE2 calculated volume at the location of the dams)." The Task Force supplied the project team with the relevant SYE2 results shown in Table 4-5, which identifies the magnitude of those requested changes and the affected sub-basins. Those impacts were incorporated into the existing conditions baseline (Scenario 0B) to reflect zero flow out of the Middleton Pond and Emerson Brook Reservoir dams during August and then removed under Scenario 3 (and 6) to represent the cessation of withdrawals from those surface water reservoirs and the return of unimpacted flows over these same two dams in August.

As explained by Task Force members, this methodology is intended to reflect the fact that operators of the surface water reservoirs report that during most summers, the stream channels immediately downstream of the reservoirs appear visually to have no flow. This Task Force-requested methodology was developed to mimic the return of August flows if surface water withdrawals were eliminated, and run-of-river conditions were re-established.

In contrast, the project team is of the opinion that, within the constraints and limitations of how a mass balance model like IRSWAM works, reservoir withdrawals have similar effects on streamflow conditions as do groundwater wells located in very near proximity to the river or its tributaries. Many groundwater wells incorporated into the model are located within 200 feet of ponds, wetlands, or other impoundments. We know through the response coefficient methodology that these close proximity wells function similarly in the model to direct surface water withdrawals. Water seepage and leakage through and around the dam can be a significant contributor to groundwater derived baseflow beneath the dam and, since withdrawals from a reservoir reduce the head difference driven transfer of water from the reservoir to the surrounding aquifer, reservoir withdrawals reduce the quantity of that transfer to groundwater and the consequent amount of groundwater available to support downstream baseflow. This issue is identified as the number one limitation to evaluating a dam's downstream impact by focusing only on spillway discharge in the USGS' Scientific Investigations Report 2016-5123 entitled "Effects of Water-Supply Reservoirs on Streamflow in Massachusetts," written by Sara Levin in 2016.

The methodology selected by the Task Force to model changes in surface water withdrawals does not capture the lingering impact of withdrawals at times of year when the three dams' spillways are flowing or the impact of water transferred into one or more of the reservoirs to refill them faster than their immediate drainage areas would allow. These withdrawals and discharges that occur when the spillways are flowing impact the level or water table elevation of the groundwater aquifers surrounding the three reservoirs, and the associated ability of that groundwater to provide baseflow, impacts that linger for several months and affect downstream streamflow. It is the project team's professional opinion that if the Scenario 3 changes to surface water withdrawal points were modeled in the same manner as are groundwater sources, it is highly likely their downstream impacts would be modeled significantly greater.

4.3 Watershed Scale Results

Each of the six theoretical water supply alternatives were evaluated with IRSWAM and compared against an existing conditions baseline (Scenario 0B) defined with the updated withdrawal data (2018-2022) provided by IRWA based on Annual Statistical Reports submitted by the respective suppliers. The model's outputs are summarized at a watershed scale in Tables 4-8A and 4-8B.

Table 4-8A: Watershed-Wide Weighted Averages of IRSWAM Outputs

Scenario*	Flow Alteration	GWC	Net GW Depletion	BC	August Median Affected Flow (cfsm)
0B	27.50%	2.82	3.10%	4.48	0.182
1	14.50%	2.12	-10.00%	4.48	0.210
2	26.70%	2.8	2.20%	4.48	0.184
3	27.50%	2.82	3.00%	4.48	0.189
4	25.90%	2.75	1.40%	4.45	0.186
5	21.60%	2.67	-2.90%	4.46	0.194
6	6.00%	1.79	-18.40%	4.37	0.233

*Scenario 0B refers to the updated baseline with public drinking water withdrawals estimated from 2018-2022 data. The other scenarios represent the cessation of pumping by town(s) as follows: 1 - Wilmington, 2 – Lynnfield, 3 – Danvers-Middleton, 4 - Topsfield & Ipswich, 5 - Wenham, Hamilton & Ipswich, and 6 – combination of all other scenarios.

Table 4-8B: Change from Baseline in Watershed-Wide Weighted Averages of IRSWAM Outputs

Scenario**	Δ Flow Alteration*	Δ GWC*	Δ Net GW Depletion*	Δ BC*	Δ August Median Affected Flow (cfsm)
0B	-	-	-	-	-
1	-13.1%	-0.70	-13.1%	-0.00	+0.028 (+15.3%)
2	-0.9%	-0.01	-0.9%	-0.00	+0.002 (+1.1%)
3	-0.1%	0.00	-0.1%	-0.00	+0.007 (+3.6%)
4	-1.7%	-0.07	-1.7%	-0.03	+0.003 (+1.8%)
5	-5.9%	-0.15	-5.9%	-0.02	+0.011 (+6.3%)
6	-21.5%	-1.03	-21.5%	-0.11	+0.051 (+28.0%)

* Percent changes are only provided for August Median Affected Flow. Values for flow alteration and Net GW Depletion reflect the absolute change in the metric, itself a percentage. GWC and BC are unitless quantities which do not reflect logically as percentages. Note that reductions in flow alteration, GWC, Net GW Depletion, and BC reflect increased streamflow.

**Scenario 0B refers to the updated baseline with public drinking water withdrawals estimated from 2018-2022 data. The other scenarios represent the cessation of pumping by town(s) as follows: 1 - Wilmington, 2 – Lynnfield, 3 – Danvers-Middleton, 4 - Topsfield & Ipswich, 5 - Wenham, Hamilton & Ipswich, and 6 – combination of all other scenarios.

Modeled changes to flow metrics for any scenario occur within the sub-basin(s) in which the withdrawals are altered and in those hydraulically connected sub-basins downstream of those containing the altered withdrawals (these are generally mainstem segments). No changes to flow metrics are modeled to occur for sub-basins upstream of the altered withdrawals, or for downstream tributary subbasins whose flows are unaffected by the altered withdrawals. The modeled "watershed-wide" averages are derived from the values of both the subbasins affected by the altered withdrawals and those unaffected by the altered withdrawals.

As expected, Scenario 6, a combination of the other five scenarios, and its 4.631-MGD reduction in withdrawals (4.116 MGD reduction in groundwater pumping and 0.521 MGD reduction in surface water pumping from Middleton Pond and Emerson Brook Reservoirs), produced the greatest modeled improvements, reducing Flow Alteration from 27.5 to 6.0% and as a result reducing the Groundwater Withdrawal Category from 2.82 to 1.79 and improving the Biological Category from 4.48 to 4.37. Net Groundwater Depletion was reduced from a 3.1% deficit across the watershed to a surplus of 18.4%. August Median Affected Flows, as calculated for each subbasin by applying the net change in both groundwater and surface water withdrawals and discharges to the SYE2-identified August median unaffected flows, increased from a basin-wide area-weighted average of 0.182 cfsm to 0.233 cfsm, a 28.0% improvement.

More interesting, however, is the effectiveness of Scenario 1 on its own. With the highest groundwater pumping reduction among Scenarios 1 through 5 at 1.837 MGD, and the affected wells' location in the headwaters of the Ipswich River watershed, Scenario 1 produces a strong benefit that literally trickles down to and through the rest of the watershed, having an outsized impact. Scenario 1 is responsible for approximately 55% of the modeled improvement to August Median Affected Flows, 60% of the modeled improvement to Flow Alteration and Net Groundwater Depletion, and 70% of the modeled improvement in average GWC achieved under Scenario 6, despite representing only 40% of Scenario 6's groundwater withdrawal reductions.

By contrast, Scenario 5 which incorporated the second greatest reduction in groundwater pumping, 1.265 MGD or 27% of Scenario 6's groundwater withdrawal reductions, was responsible for approximately 15% of the Scenario 6 improvement to GWC, 20% of the improvement to August Median Affected Flow, and approximately 30% of the improvements to Flow Alteration and Net Groundwater Depletion achieved under Scenario 6.

As expected, Scenarios 2 and 4, which consist of smaller reductions in groundwater pumping, produce significantly smaller benefits in the context of IRSWAM outputs. For example, none of the smaller reductions proposed under those scenarios is capable of improving the watershed's modeled average Flow Alteration or Net Groundwater Depletion by more than 1%.

Scenario 3 includes the cessation of relatively modest pumping from a single groundwater source and the cessation of significantly greater withdrawals from two surface water reservoirs. It is important to note that IRSWAM's modeled changes to WMA metrics, like flow alteration and net groundwater depletion, are affected only by cessation of pumping from the groundwater well. This modest change in pumping is reflected in correspondingly modest changes to WMA metrics. However, Scenario 3's more significant elimination of surface water withdrawals is reflected in IRSWAM's much more significant predicted changes in August Median Affected Flow, where Scenario 3 outperforms both Scenario 2 and 4.

Given the strong correlation between reduced withdrawal rates and benefits to the Ipswich River and its watershed, and the fact that if pumping is reduced that drinking water must be supplied and/or purchased from outside the watershed, it is useful to understand how those benefits compare between scenarios on a per MGD reduced basis. Table 4-9 presents such normalized model outputs for several key outputs. That table can be interpreted as indicative of which scenarios are most efficient or provide literally the greatest "bang" or benefit "for your buck."

Table 4-9: Normalized Watershed and Streamflow Changes

Scenario**	Reduction in Pumping (MGD)	Δ Flow Alteration / Net GW Depletion (%)*	Δ August Median Affected Flow (%)*
0B	---	---	---
1	1.664	7.1%	8.3%
2	0.413	1.9%	2.5%
3	0.895	0.1%	6.0%
4	0.682	1.3%	2.6%
5	1.143	4.7%	5.0%
6	4.574	4.6%	6.0%

*Changes were divided by each scenario's total reduction in groundwater or surface water withdrawals in the watershed to normalize results between scenarios.

**Scenario 0B refers to the updated baseline with public drinking water withdrawals estimated from 2018-2022 data. The other scenarios represent the cessation of pumping by town(s) as follows: 1 - Wilmington, 2 – Lynnfield, 3 – Danvers-Middleton, 4 - Topsfield & Ipswich, 5 - Wenham, Hamilton & Ipswich, and 6 – combination of all other scenarios.

Table 4-10 confirms that even when benefits are normalized, Scenario 1 continues to reduce Flow Alteration and Net Groundwater Depletion significantly more than other scenarios. It also improves August Median Affected Flows more than other scenarios, although perhaps not quite as dramatically. Scenario 5 continues to perform second best across the WMA metrics and third best with regard to August Median Affected Flow. Scenario 3, by definition, has very little impact on Flow Alteration or Net Groundwater Depletion, but it does produce the second greatest improvement to August Median Affected Flows. Scenarios 2 and 4 continue to produce lesser benefits.

4.4 Sub-Basin Scale Results

Naturally, the benefits of these scenarios are experienced differently throughout the watershed. This section presents some of the sub-basin scale nuances of the various water supply alternatives in the context of the four WMA metrics and August Median Affected Flows. Those five IRSWAM model outputs are summarized tabularly on a sub-basin basis in Tables 4-10 through 4-14, below.

Table 4-10: Net Groundwater Depletion (%) by Scenario at a Sub-Basin Scale**

Sub-Basin ID	Scenario 0B	Scenario 1	Scenario 2	Scenario 3*	Scenario 4	Scenario 5	Scenario 6*
21001	20%	no change	no change	no change	-2%	no change	-2%
21002	5%	-4%	3%	no change	3%	0%	-15%
21003	60%	no change	no change	no change	-15%	no change	-15%
21004	262%	no change	no change	no change	no change	-28%	-28%
21005	-1%	-13%	-4%	-2%	no change	no change	-17%
21006	-14%	no change	no change	no change	no change	no change	no change
21007	6%	-3%	4%	no change	4%	1%	-14%
21008	-7%	no change	no change	no change	no change	no change	no change
21009	30%	no change	no change	no change	0%	no change	0%
21012	-17%	no change	no change	no change	no change	no change	no change
21013	5%	-21%	-1%	no change	no change	no change	-28%
21018	-20%	no change	no change	no change	no change	no change	no change
21019	4%	-19%	-2%	3%	no change	no change	-25%
21020	-12%	no change	no change	no change	no change	no change	no change
21021	2%	-18%	-3%	no change	no change	no change	-24%
21031	-5%	no change	no change	no change	-11%	-13%	-13%
21032	-11%	no change	no change	no change	no change	no change	no change
21041	-13%	no change	no change	no change	no change	no change	no change
21065	2%	no change	no change	no change	no change	no change	no change
21066	5%	-4%	2%	4%	3%	0%	-14%
21067	-16%	no change	no change	no change	no change	no change	no change
21068	-13%	no change	no change	no change	no change	-15%	-15%
21069	-12%	no change	no change	no change	no change	no change	no change
21070	-5%	no change	no change	no change	no change	no change	no change
21071	0%	-15%	-4%	-1%	no change	no change	-20%
21072	-15%	no change	no change	no change	no change	no change	no change
21073	46%	-29%	no change	no change	no change	no change	-29%
21074	-22%	-36%	no change	no change	no change	no change	-36%
21076	9%	-57%	no change	no change	no change	no change	-57%
21077	-20%	no change	no change	no change	no change	no change	no change
21217	3%	-4%	1%	no change	1%	-2%	-13%
Watershed-Wide Weighted Average	3%	-10%	2%	3%	1%	-3%	-18%
# Changed	---	12	9	4	8	7	18

Note: Highlighted cells indicate sub-basins with improved Net Groundwater Depletion.

*Scenarios 3 and 6's reductions in surface water withdrawals have no impact on Net Groundwater Depletion as that WMA metric is affected by changes to groundwater withdrawals and discharges only.

**Scenario 0B refers to the updated baseline with public drinking water withdrawals estimated from 2018-2022 data. The other scenarios represent the cessation of pumping by town(s) as follows: 1 - Wilmington, 2 – Lynnfield, 3 – Danvers-Middleton, 4 - Topsfield & Ipswich, 5 - Wenham, Hamilton & Ipswich, and 6 – combination of all other scenarios.

Table 4-11: Flow Alteration (%) by Scenario** at a Sub-Basin Scale

Sub-Basin ID	Scenario 0B	Scenario 1	Scenario 2	Scenario 3*	Scenario 4	Scenario 5	Scenario 6*
21001	37%	no change	no change	no change	15%	no change	15%
21002	26%	16%	23%	25%	24%	21%	6%
21003	80%	no change	no change	no change	4%	no change	4%
21004	291%	no change	no change	no change	no change	1%	1%
21005	21%	9%	18%	no change	no change	no change	6%
21006	2%	no change	no change	no change	no change	no change	no change
21007	25%	16%	23%	no change	23%	20%	5%
21008	6%	no change	no change	no change	no change	no change	no change
21009	49%	no change	no change	no change	19%	no change	19%
21012	1%	no change	no change	no change	no change	no change	no change
21013	36%	10%	29%	no change	no change	no change	3%
21018	7%	no change	no change	no change	no change	no change	no change
21019	32%	10%	27%	no change	no change	no change	4%
21020	12%	no change	no change	no change	no change	no change	no change
21021	30%	10%	25%	no change	no change	no change	4%
21031	9%	no change	no change	no change	3%	1%	1%
21032	1%	no change	no change	no change	no change	no change	no change
21041	11%	no change	no change	no change	no change	no change	no change
21065	19%	no change	no change	no change	no change	no change	no change
21066	24%	16%	22%	no change	22%	19%	6%
21067	1%	no change	no change	no change	no change	no change	no change
21068	4%	no change	no change	no change	no change	2%	2%
21069	10%	no change	no change	no change	no change	no change	no change
21070	14%	no change	no change	no change	no change	no change	no change
21071	24%	9%	21%	no change	no change	no change	5%
21072	9%	no change	no change	no change	no change	no change	no change
21073	77%	2%	no change	no change	no change	no change	2%
21074	17%	2%	no change	no change	no change	no change	2%
21076	78%	12%	no change	no change	no change	no change	12%
21077	3%	no change	no change	no change	no change	no change	no change
21217	22%	14%	20%	21%	19%	16%	5%
Watershed-Wide Weighted Average	28%	15%	27%	no change	26%	22%	6%
# Changed	---	12	9	2	8	7	18

Note: Highlighted cells indicate sub-basins with improved Flow Alteration.

*Scenarios 3 and 6's reductions in surface water withdrawals have no impact on Flow Alteration as that WMA metric is affected by changes to groundwater withdrawals and discharges only.

**Scenario 0B refers to the updated baseline with public drinking water withdrawals estimated from 2018-2022 data. The other scenarios represent the cessation of pumping by town(s) as follows: 1 - Wilmington, 2 – Lynnfield, 3 – Danvers-Middleton, 4 - Topsfield & Ipswich, 5 - Wenham, Hamilton & Ipswich, and 6 – combination of all other scenarios.

Table 4-12: Groundwater Withdrawal Category by Scenario at a Sub-Basin Scale**

Sub-Basin ID	Scenario 0B	Scenario 1	Scenario 2	Scenario 3*	Scenario 4	Scenario 5	Scenario 6*
21001	4	no change	no change	no change	3	no change	3
21002	4	3	3	no change	3	3	2
21003	5	no change	no change	no change	2	no change	2
21004	5	no change	no change	no change	no change	1	1
21005	3	2	no change	no change	no change	no change	2
21006	1	no change	no change	no change	no change	no change	no change
21007	3	no change	no change	no change	no change	no change	2
21008	2	no change	no change	no change	no change	no change	no change
21009	4	no change	no change	no change	3	no change	3
21012	1	no change	no change	no change	no change	no change	no change
21013	4	2	no change	no change	no change	no change	1
21018	2	no change	no change	no change	no change	no change	no change
21019	4	3	no change	no change	no change	no change	2
21020	3	no change	no change	no change	no change	no change	no change
21021	4	2	no change	no change	no change	no change	2
21031	2	no change	no change	no change	no change	1	1
21032	1	no change	no change	no change	no change	no change	no change
21041	3	no change	no change	no change	no change	no change	no change
21065	3	no change	no change	no change	no change	no change	no change
21066	3	no change	no change	no change	no change	no change	2
21067	1	no change	no change	no change	no change	no change	no change
21068	2	no change	no change	no change	no change	1	1
21069	3	no change	no change	no change	no change	no change	no change
21070	3	no change	no change	no change	no change	no change	no change
21071	3	2	no change	no change	no change	no change	2
21072	2	no change	no change	no change	no change	no change	no change
21073	5	1	no change	no change	no change	no change	1
21074	3	1	no change	no change	no change	no change	1
21076	5	3	no change	no change	no change	no change	3
21077	1	no change	no change	no change	no change	no change	no change
21217	3	no change	no change	no change	no change	no change	2
Watershed-Wide Weighted Average	2.82	2.12	2.80	no change	2.75	2.67	1.79
# Changed	---	9	1	0	3	4	18

Note: Highlighted cells indicate sub-basins with improved GWCs.

*Scenarios 3 and 6's reductions in surface water withdrawals have no impact on GWC as that WMA metric is affected by changes to groundwater withdrawals and discharges only.

**Scenario 0B refers to the updated baseline with public drinking water withdrawals estimated from 2018-2022 data. The other scenarios represent the cessation of pumping by town(s) as follows: 1 - Wilmington, 2 – Lynnfield, 3 – Danvers-Middleton, 4 - Topsfield & Ipswich, 5 - Wenham, Hamilton & Ipswich, and 6 – combination of all other scenarios.

Table 4-13: Biological Category by Scenario at a Sub-Basin Scale**

Sub-Basin ID	Scenario 0B	Scenario 1	Scenario 2	Scenario 3*	Scenario 4	Scenario 5	Scenario 6*
21001	5	no change	no change	no change	4	no change	4
21002	5	no change	no change	no change	no change	no change	4
21003	5	no change	no change	no change	4	no change	4
21004	5	no change	no change	no change	no change	4	4
21005	5	no change	no change	no change	no change	no change	no change
21006	3	no change	no change	no change	no change	no change	no change
21007	5	no change	no change	no change	no change	no change	4
21008	4	no change	no change	no change	no change	no change	no change
21009	5	no change	no change	no change	4	no change	4
21012	5	no change	no change	no change	no change	no change	no change
21013	5	no change	no change	no change	no change	no change	no change
21018	4	no change	no change	no change	no change	no change	no change
21019	5	no change	no change	no change	no change	no change	no change
21020	4	no change	no change	no change	no change	no change	no change
21021	5	no change	no change	no change	no change	no change	no change
21031	4	no change	no change	no change	no change	no change	no change
21032	4	no change	no change	no change	no change	no change	no change
21041	4	no change	no change	no change	no change	no change	no change
21065	4	no change	no change	no change	no change	no change	no change
21066	5	no change	no change	no change	no change	no change	4
21067	3	no change	no change	no change	no change	no change	no change
21068	4	no change	no change	no change	no change	no change	no change
21069	4	no change	no change	no change	no change	no change	no change
21070	4	no change	no change	no change	no change	no change	no change
21071	5	no change	no change	no change	no change	no change	no change
21072	4	no change	no change	no change	no change	no change	no change
21073	5	no change	no change	no change	no change	no change	no change
21074	5	no change	no change	no change	no change	no change	no change
21076	5	no change	no change	no change	no change	no change	no change
21077	5	no change	no change	no change	no change	no change	no change
21217	5	no change	no change	no change	no change	no change	4
Watershed-Wide Weighted Average	4.48	no change	no change	no change	4.45	4.46	4.37
# Changed	---	0	0	0	3	1	8

Note: Highlighted cells indicate sub-basins with improved BCs.

*Scenarios 3 and 6's reductions in surface water withdrawals have no impact on BC as that WMA metric is affected by changes to groundwater withdrawals and discharges only.

**Scenario 0B refers to the updated baseline with public drinking water withdrawals estimated from 2018-2022 data. The other scenarios represent the cessation of pumping by town(s) as follows: 1 - Wilmington, 2 – Lynnfield, 3 – Danvers-Middleton, 4 - Topsfield & Ipswich, 5 - Wenham, Hamilton & Ipswich, and 6 – combination of all other scenarios.

Table 4-14: August Median Affected Flow (cfsm) by Scenario** at a Sub-Basin Scale

Sub-Basin ID	Scenario 0B	Scenario 1	Scenario 2	Scenario 3*	Scenario 4	Scenario 5	Scenario 6
21001	0.172	no change	no change	no change	0.219	no change	0.219
21002	0.224	0.248	0.230	0.232	0.231	0.237	0.280
21003	0.072	no change	no change	no change	0.209	no change	0.209
21004	-0.304	no change	no change	no change	no change	0.240	0.240
21005	0.232	0.261	0.239	0.242	no change	no change	0.277
21006	0.203	no change	no change	no change	no change	no change	no change
21007	0.223	0.246	0.229	0.231	0.230	0.236	0.278
21008	0.204	no change	no change	no change	no change	no change	no change
21009	0.147	no change	no change	no change	0.210	no change	0.210
21012	0.246	no change	no change	no change	no change	no change	no change
21013	0.222	0.284	0.238	no change	no change	no change	0.300
21018	0.081	no change	no change	0.191	no change	no change	0.191
21019	0.231	0.284	0.244	0.233	no change	no change	0.299
21020	0.062	no change	no change	0.147	no change	no change	0.147
21021	0.227	0.276	0.239	0.235	no change	no change	0.297
21031	0.220	no change	no change	no change	0.235	0.239	0.239
21032	0.185	no change	no change	no change	no change	no change	no change
21041	0.180	no change	no change	no change	no change	no change	no change
21065	0.199	no change	no change	no change	no change	no change	no change
21066	0.229	0.251	0.234	0.236	0.236	0.241	0.281
21067	0.234	no change	no change	no change	no change	no change	no change
21068	0.229	no change	no change	no change	no change	0.234	0.234
21069	0.171	no change	no change	no change	no change	no change	no change
21070	0.202	no change	no change	no change	no change	no change	no change
21071	0.226	0.262	0.235	0.238	no change	no change	0.282
21072	0.178	no change	no change	no change	no change	no change	no change
21073	0.115	0.277	no change	no change	no change	no change	0.277
21074	0.245	0.275	no change	no change	no change	no change	0.275
21076	0.177	0.296	no change	no change	no change	no change	0.296
21077	0.231	no change	no change	no change	no change	no change	no change
21217	0.236	0.255	0.241	0.243	0.244	0.249	0.284
Watershed-Wide Weighted Average	0.182	0.210	0.184	0.189	0.186	0.194	0.233
# Changed	---	12	9	10	8	7	20

Note: Highlighted cells indicate sub-basins with improved August Median Affected Flows.

*Scenarios 3 and 6's reductions in surface water withdrawals do impact IRSWAM's August Median Affected Flow output.

**Scenario 0B refers to the updated baseline with public drinking water withdrawals estimated from 2018-2022 data. The other scenarios represent the cessation of pumping by town(s) as follows: 1 - Wilmington, 2 – Lynnfield, 3 – Danvers-Middleton, 4 - Topsfield & Ipswich, 5 - Wenham, Hamilton & Ipswich, and 6 – combination of all other scenarios.

Net Groundwater Depletion is one of the most telling outputs of the WMA Tool and, consequently, IRSWAM, particularly in how it distinguishes between resources that are withdrawn but not returned until significantly further downstream or perhaps into another watershed entirely. Therefore, in an effort to streamline the results of this evaluation, maps identifying the spatial distribution of the six scenarios' benefits have focused on this particularly telling output. Sub-basin scale changes in Net Groundwater Depletion are shown visually in Figures 5 through 10.

4.5 Key Findings

Based on the results presented above in Sections 4.3 and 4.4, the project team has identified the following key findings regarding its evaluation of the six water supply alternatives identified by the North Shore Water Resilience Task Force:

- Significant changes (48% reduction in public and commercial groundwater withdrawals) have already occurred over the past two decades. Based on the below WMA threshold water use estimates from the MassDEP Below WMA Threshold Study (MassDEP, 2018), public/commercial groundwater withdrawals now represent 79% (down from the 95% reported in the 2018 MassDEP study) of all groundwater withdrawals in the watershed. Note that the IRWA 2019 critique of the MassDEP study claims that below threshold water use is significantly higher than reported in the MassDEP 2018 study. Per that claim, the current significance of public/commercial groundwater withdrawals would now represent less than 79%. Reportedly Task Force members, including DEP, have coalesced on a more recent opinion that the significance of below WMA threshold withdrawals is likely greater than reported in the 2018 DEP study.
- Those public and commercial groundwater reductions have significantly improved modeled baseline conditions as seen in all WMA metrics and August Median Affected Flows in most areas of the watershed, particularly the upper half of the watershed.
- Scenario 6 naturally produces the greatest modeled benefits as it represents the combination of all other scenarios. It reduces Flow Alteration from 27.5 to 6.0%, the Net Groundwater Category from 2.82 to 1.79, and the Biological Category from 4.48 to 4.37. August Median Affected Flows were estimated to increase from 0.182 to 0.233 cfsm when averaged across the watershed.
- Scenario 1 is the most efficient (i.e., in terms of improvement per MGD withdrawal reduction) of the five base alternatives through the lens of all model outputs. With the highest reduction in drinking water withdrawals and the affected wells' location in the headwaters of the Ipswich River watershed, it produces a strong trickle-down benefit. Scenario 1 is responsible for approximately 55% of the improvement to August Median Affected Flows, 60% of the improvement to Flow Alteration and Net Groundwater Depletion, and 70% of the improvement in average GWC achieved under Scenario 6, despite representing only 37% of Scenario 6's groundwater withdrawal reductions.
- Scenario 5 generally finishes second best, responsible for approximately 15% of the Scenario 6 improvement to GWC, 20% of the improvement to August Median Affected Flow, and approximately 30% of the improvements to Flow Alteration and Net Groundwater Depletion achieved under Scenario 6.
- The benefits achieved under Scenarios 2 and 4 are generally an order of magnitude smaller than Scenario 1. Even when normalized to reflect their smaller reduction in pumping rates, they are still significantly less effective or efficient than Scenarios 1 and 5.
- Model outputs indicate that while Scenario 3's limited reductions in groundwater withdrawals have a very modest impact on WMA metrics, its more significant reductions in effective surface water withdrawals may significantly improve August Median Affected Flows in the watershed. While surface

water/groundwater dynamics around reservoirs are complicated and time variable, please note that, as discussed in detail in Section 4.2, it is the project team's professional opinion that the Task Force requested methodology used to represent Scenario 3 in the model may result in an underestimation of the potential flow benefits that could be achieved under this scenario.

5.0 CONCLUSION

The novel IRSWAM model described in this report represents a significant additional step in a growing body of investigations, research, and modeling focused on the Ipswich River watershed. IRSWAM builds upon the methods and data incorporated in the WMA Tool and MASYE, combining the function of these tools and expanding their collective capabilities by incorporating the ability to model scenarios involving specific withdrawal and discharge points. Groundwater withdrawal input data utilized by the WMA Tool was supplemented with updated information from recent Annual Statistical Reports compiled by IRWA where available, further improving the applicability of results using the WMA Tool methodology and allowing for the impacts of recent historical changes in withdrawal patterns to be assessed. These tools themselves are built upon expansive and thorough previous scientific efforts related to the Ipswich and similar watersheds, without which this effort would not have been possible.

IRSWAM improves upon the capabilities of the WMA Tool and MASYE in two key ways, in addition to combining their functions. First, specific withdrawal and discharge points can be altered within the model, and the timing of withdrawals can be manipulated within IRSWAM. This granular control over modeled scenarios allows for analysis of detailed, specific water management alternatives. Second, IRSWAM calculates cumulative downstream impacts of alternatives. Combining these two improvements allows for direct comparison of the net benefits of alternatives at the basin and sub-basin scales. The outputs of IRSWAM are calculated and reported using the same well-established and interpretable metrics established in the WMA Tool. The granularity of inputs and results allow for direct comparison of the relative efficiency of various modeled scenarios.

The project team used IRSWAM to evaluate five water supply alternatives or scenarios plus a sixth scenario that combined all five alternatives, as identified and defined by the Task Force. For each sub-basin under each scenario, IRSWAM produces the resulting metrics from the WMA Tool including Flow Alteration, GWC, BC, and Net Groundwater Depletion. In addition, the model evaluates the anticipated change in August median flow conditions in each sub-basin based on the anticipated groundwater and surface water changes to the mass balance of that sub-basin and all upstream sub-basins and from SYE2- derived estimate of August Median Unaffected Flow.

The detailed results for each scenario are presented in full in sections 4.3 and 4.4 above. Scenario 0B represents updated recent withdrawal information, compared to original WMA Tool inputs (Scenario 0A) from the 2000-2004 time period. This updated data indicates that in-watershed public groundwater withdrawal has decreased significantly over the past two decades, and associated modeled improvements have resulted from this change. Modeled improvements include significant reduction in flow alteration and net groundwater depletion, a decrease in weighted average GWC and BC, and an increase in August median flows. Subsequent water supply alternative scenarios were assessed relative to this modified baseline. As noted in multiple sections above, particularly those that discuss MassDCR's analysis of Ipswich River streamflow data, some portion of the documented decline in WMA-regulated groundwater withdrawals has likely been offset by increased reservoir and private well withdrawals that are not captured in the available data for the WMA Tool or IRSWAM and, therefore, real world streamflow benefits may be less than those modeled and discussed herein.

Supply alternative scenarios represent options for decreased water supply withdrawn from the Ipswich River Watershed. Unsurprisingly, the largest reductions in withdrawal yielded the highest level of improvement at the watershed scale. The granular inputs and outputs of IRSWAM allow for more detailed comparison of the relative benefits of specific alternatives. Model results indicate that reductions in upstream, headwaters watersheds yield greater positive impacts throughout the watershed. The benefit of reducing withdrawal, and thus increasing streamflows, in upstream sub-basins cascades down to the rest of the watershed. Calculating the relative magnitude of this cascading benefit is a novel result of IRSWAM compared to its predecessors.

6.0 REFERENCES

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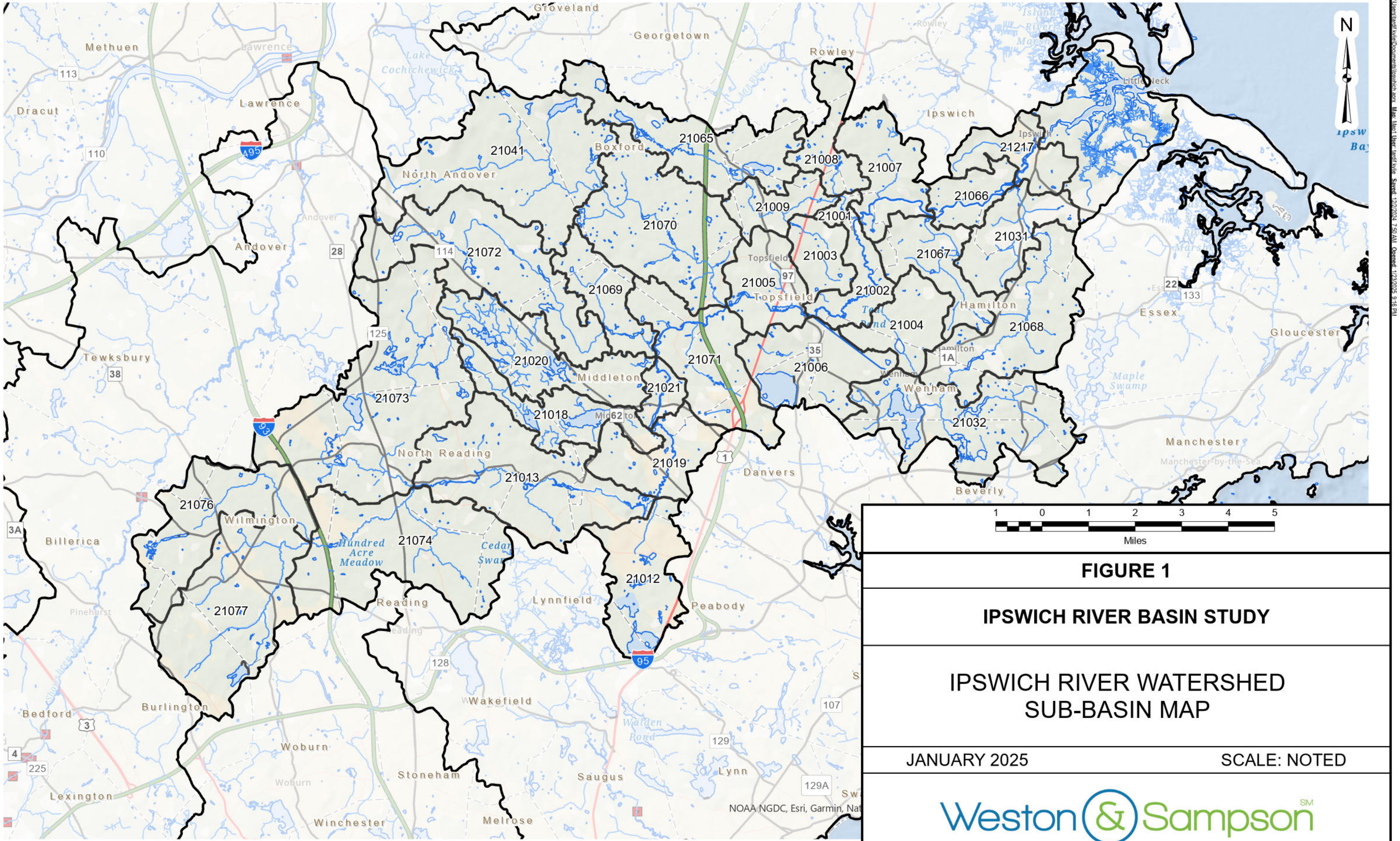
FIGURES



1 0 1 2 3 4 5

Miles

FIGURE 1

IPSWICH RIVER BASIN STUDY

IPSWICH RIVER WATERSHED SUB-BASIN MAP

JANUARY 2025

SCALE: NOTED

Weston & Sampson℠

Path: C:\Users\tardif.kylie\Documents\Ipswhich.aprx Map: Map1 User: tardif.kylie Saved: 12/2/2024 7:50 AM Opened: 1/23/2025 9:16 PM

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

FIGURE 2A

IPSWICH RIVER
WATERSHED ASSOCIATION

SWMI GROUNDWATER WITHDRAWAL CATEGORY (SCENARIO 0A)

SEPTEMBER 2024

SCALE: NOTED

Weston & Sampson℠

Path: C:\Users\tardif.kylie\Documents\Ipswhich.aprx Map: Figure 1A - SWMI Estimated Aug GW Flow Alteration (GWC) Map User: tardif.kylie Saved: 9/23/2024 3:32 PM Opened: 10/23/2024 7:38 AM

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

NOAA, NGDC, Esri, Garmin, Natural

FIGURE 2B

IPSWICH RIVER WATERSHED ASSOCIATION

SWMI GROUNDWATER WITHDRAWAL CATEGORY (SCENARIO 0B)

SEPTEMBER 2024 SCALE: NOTED

Weston & Sampson℠

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

FIGURE 3A

IPSWICH RIVER WATERSHED ASSOCIATION

FLOW ALTERATION
(SCENARIO 0A)

SEPTEMBER 2024 SCALE: NOTED

Weston & Sampson

NOAA NGDC, Esri, Garmin, Natur

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

FIGURE 3B

IPSWICH RIVER
WATERSHED ASSOCIATION

FLOW ALTERATION
(SCENARIO 0B)

SEPTEMBER 2024 SCALE: NOTED

Weston & Sampson℠

Path: C:\Users\tardif.kylie\Documents\Ipswhich.aprx **Map:** Figure 2B - SWMI Estimated Aug GW Withdrawals (PA) **User:** tardif.kylie **Saved:** 10/24/2024 9:48 AM **Opened:** 10/24/2024 10:06 AM

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

FIGURE 4A

IPSWICH RIVER WATERSHED ASSOCIATION

NET DEPLETION
(SCENARIO 0A)

SEPTEMBER 2024 | SCALE: NOTED

Weston & Sampson

Path: C:\Users\tardif.kylie\Documents\Ipswhich.aprx **Map:** SWMI Estimated Aug GW Depletion Map **User:** tardif.kylie **Saved:** 10/24/2024 9:48 AM **Opened:** 10/24/2024 10:09 AM

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

FIGURE 4B

IPSWICH RIVER
WATERSHED ASSOCIATION

NET DEPLETION
(SCENARIO 0B)

SEPTEMBER 2024 SCALE: NOTED

Weston & Sampson

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

FIGURE 5

IPSWICH RIVER
WATERSHED ASSOCIATION

NET GW DEPLETION
(SCENARIO 1)

MAY 2024 SCALE: NOTED

Weston & Sampson

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

FIGURE 6

IPSWICH RIVER WATERSHED ASSOCIATION

NET GW DEPLETION (SCENARIO 2)

MAY 2024 SCALE: NOTED

Weston & Sampson

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

FIGURE 7

**IPSWICH RIVER
WATERSHED ASSOCIATION**

NET GW DEPLETION
(SCENARIO 3)

MAY 2024

SCALE: NOTED

Weston & Sampson

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

NOAA NGDC, Esri, Garmin, Natural

FIGURE 8

IPSWICH RIVER WATERSHED ASSOCIATION

NET GW DEPLETION
(SCENARIO 4)

MAY 2024 SCALE: NOTED

Weston & Sampson℠

FIGURE 9

IPSWICH RIVER
WATERSHED ASSOCIATION

NET GW DEPLETION
(SCENARIO 5)

MAY 2024 SCALE: NOTED

Weston & Sampson℠

datasource: Groundwater Withdrawal Category (GWC) August 2013 data

FIGURE 10

IPSWICH RIVER
WATERSHED ASSOCIATION

NET GW DEPLETION
(SCENARIO 6)

MAY 2024 SCALE: NOTED

Weston & Sampson

APPENDIX A

Memorandum: Task 1 Literature Review Summary Memorandum - Ipswich River Watershed Water Supply Alternatives Modeling Project

Horsley Witten Group and Weston & Sampson Engineers, November 30, 2023