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An Extension of Migration Effectiveness Indices: Accounting for the Impact of Migration on Population Structure

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ABSTRACT

This study introduces the age-weighted migration effectiveness index (AWMEI), a new metric that integrates age-specific variation into a single measure of migration effectiveness. Traditional indices, such as the migration effectiveness index (MEI) and age-specific MEI (ASMEI), effectively address the first aspect of migration effectiveness—population redistribution—but overlook the second aspect—transformation of the composition of regional populations. The AWMEI bridges this gap by weighting net migration flows according to their age structure, offering comprehensive insights into migration's dual impacts. Applied to South Korea's internal migration data (2001–2022), the AWMEI uncovers patterns previously obscured by conventional measures. Nationally, an increasing divergence between AWMEI and MEI reveals growing age disparities in migration patterns. At regional and local scales, the AWMEI highlights substantial age-specific population shifts even where traditional indices indicate minimal migration effectiveness. Amid broader spatial demographic transitions, the AWMEI provides a robust analytical framework for capturing migration's demographic implications. Its inherent adaptability further allows broad application across diverse dimensions of population composition and various research contexts.

1 | Introduction

As spatial variations in fertility and mortality have diminished, internal migration has increasingly become the dominant demographic process driving population redistribution, particularly in countries where international migration remains relatively low (Stillwell et al. 2001). Since it is not merely the exchange of populations but the asymmetry in these exchanges that drives changes in the geographic arrangement of population (Plane 1994), much attention has been devoted to conceptualizing and measuring the unidirectionality of internal migration. In this context, the concept of migration effectiveness is crucial. Although the notion was first introduced decades ago (Shryock 1964; Thomas 1941), its operationalization for empirical research was advanced by Plane (1984, 1994), who formulated a set of migration effectiveness indices (MEIs) designed to measure the degree of unidirectionality or imbalance in inter-regional migration.

However, it is important to recognize that migration can be *effective* not only in altering population distribution but also in transforming regional population structure. In other words, internal migration can lead to changes in both population size and population composition within a region (Shryock 1964);

changes in population composition can occur even without significant shifts in population size. To date, studies on migration effectiveness have primarily focused on what can be termed the *first aspect of migration effectiveness*: its impact on changes in population distribution. Our study seeks to shift attention to the *second aspect of migration effectiveness*: its impact on changes in population structure in terms of gender, age, race, ethnicity, and other demographic categories. Thus, our primary concern is to develop a viable approach for assessing the second aspect by building upon the methods used to study the first aspect.

In pursuing this, it is critical to recognize that the meaning and implications of migration effectiveness vary across different spatial scales (Plane 1984, 1994; Plane and Rogerson 1994). At a local or stream scale, a pair of regions with significant directional imbalances contribute more to population redistribution than other pairs with smaller differences. At a regional scale, a region with a larger gap between out-migration and in-migration contributes more to population redistribution than other regions where this gap is smaller. Finally, at a global scale, a population system characterized by greater overall imbalance in population exchanges among all regions exerts a more significant impact through migration compared to other systems. Thus, any attempt to devise new measures to account for the second aspect should embrace the notion of *spatial scalability* to provide a consistent set of measures which are applied to different spatial scales.

A common approach to considering population composition in migration studies has been to disaggregate the first aspect of migration effectiveness by categories such as gender, age, ethnicity, and so on. Among these categories, age is particularly important because, as Plane (1994) noted, 'some of the more interesting properties or relationships exposed by the demographic effectiveness measure arise from separate examinations of the movement of people at different stages of the life-cycle'. Age-specific migration effectiveness measures have been used to explore variations in the first aspect of migration effectiveness across different age groups (de Jong et al. 2016; Fielding 2018; Ishikawa 2020; Kotsubo and Nakaya 2024; Lomax and Stillwell 2018; Newbold 2011; Plane et al. 2005; Plane and Jurjevich 2009; Stillwell et al. 2001). This disaggregated approach has been extended to other categories, as seen in ethnicity-specific migration effectiveness (Stillwell and Hussain 2010).

The concept of age-specific migration effectiveness serves as the foundation for our attempt to develop new measures for assessing the impact of migration on population structure. This is because the age diversity observed in the first aspect of migration effectiveness is closely, though not directly, related to its second aspect. For instance, regions with significant age disparities in migration flows in terms of amount and/or sign are more likely to experience substantial changes in their population composition. Therefore, the main objective of our research is to propose a new set of MEIs that extends the original set of indices by incorporating age-specificity. Our secondary objective is to validate the practical utility of these measures by applying them to recent internal migration data from South Korea.

2 | A New Set of Migration Effectiveness Indices

To clarify our motivation for extending the original MEIs to account for the second aspect of migration effectiveness, we present a simple example involving two hypothetical regions in Figure 1. In Region A, only young people are migrating in and out, resulting in a net migration of zero. In Region B, however, young people are migrating in while only elderly people are migrating out, also resulting in a net migration of zero. Although Regions A and B are identical regarding the first aspect of migration effectiveness, they differ significantly in the second aspect. If this trend continues over time, the population size of both regions will remain unchanged. However, Region B will experience significant changes in composition, whereas Region A will remain unchanged. This highlights the need for developing new measures that can distinguish between these scenarios by extending the original MEI framework to incorporate the concept of age specificity or disparity.

2.1 | The Migration Effectiveness Index (MEI)

As Plane (1994) noted, the MEI has long been regarded as 'one of the best at standardizing migration to understand its directionality'. Over the past 30 years, empirical research has expanded significantly. Early studies focused on state-to-state migration within the United States in the 1990s (Manson and Groop 1996; Miller 1995; Plane 1994), More recently, attention has shifted towards cross-national comparisons (Bell et al. 2020; Rees et al. 2017; Stillwell et al. 2000) and investigations into migration patterns in countries beyond the USA, UK, and Australia, including China, Slovenia, Germany, Japan, and South Korea (Bonifazi and Heins 2000; Drobne and Drešček 2019; Fan 2005; Kotsubo and Nakaya 2023; S.-I. Lee and Lee 2023; Lomax 2022; Stawarz and Sander 2020). In this context, we use the MEI as a foundation for developing new measures.

The regional MEI is defined as follows (Plane 1984, 1994; Plane and Rogerson 1994; Stillwell et al. 2000):

$$MEI_i = \frac{IM_i - OM_i}{IM_i + OM_i} \times 100 = \frac{NM_i}{GM_i} \times 100, \qquad (1)$$

where IM_i is the number of total in-migrants to a region i and OM_i is the number of total out-migrants from the region. Thus, the regional MEI is basically a ratio of net migration to gross

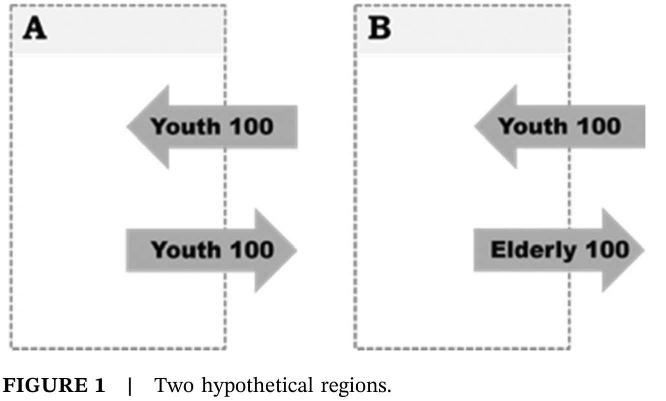

FIGURE 1 | Two hypothetical regions.

migration for a region. It ranges from −100 to 100. If the number of in-migrants and out-migrants is equal, the value is 0. If there are no out-migrants and only in-migrants, the value is 100. Conversely, if there are no in-migrants and only out-migrants, the value is −100.

An upscaling version of the regional MEI, the global MEI, is given as follows (Plane 1984, 1994; Stillwell et al. 2000):

$$MEI = \frac{\sum_i |IM_i - OM_i|}{\sum_i (IM_i + OM_i)} \times 100 = \frac{\sum_i |NM_i|}{\sum_i GM_i} \times 100. \tag{2}$$

This is what Plane (1994) called the 'system effectiveness'. This is basically a ratio of the sum of absolute net-migration or net-redistribution to the sum of gross migration for all regions in a migration system. This global MEI ranges between 0 and 100. Global-scale research typically focuses on examining temporal trends in global measures and linking them to nationwide economic conditions within a specific country (S.-I. Lee and Lee 2023; Mchugh and Gober 1992; Miller 1995; Plane 1994; Stillwell et al. 2000; Vias 2010).

A downscaling version of the regional MEI, the local MEI, is given as follows (Plane 1984, 1994; Stillwell et al. 2000):

$$MEI_{ij} = \frac{Y_{ij} - Y_{ji}}{Y_{ij} + Y_{ji}} \times 100 = \frac{NM_{ij}}{GM_{ij}} \times 100, \tag{3}$$

where Y_{ij} and Y_{ji} represent the number of people moving from region i to region j and from region j to region i, respectively. This is what Plane (1994) called the 'stream effectiveness'. This measures the net migration effectiveness at the individual region-pair level and takes a value between −100 and 100 (Mchugh and Gober 1992; Plane 1984; Vias 2010). If population exchange between two regions occurs in only one direction, a value of −100 or 100 is obtained. If the population exchange between the two regions is perfectly balanced, a value of 0 is obtained. This local or inter-regional MEI is highly important. The regional MEI reflects only the average tendency of population exchange between a given region and all other regions, while the global MEI generalizes the spatial variation indicated by regional MEIs. Different combinations of inter-regional flows can produce the same regional MEI values, and different combinations of regional MEIs can yield the same global MEI value. Despite the conceptual significance of local MEIs, there is limited research that actively explores or analyzes local MEI values (S.-I. Lee and Lee 2023; Plane 1984; Stillwell et al. 2000).

Lastly, the region-specific MEI as an in-between measure of the regional MEI_i and the local MEI_{ij} can be defined as follows (S.-I. Lee and Lee 2023):

$$MEI_{*j} = \frac{Y_{*j} - Y_{j*}}{Y_{*j} + Y_{j*}} \times 100 = \frac{NM_{*j}}{GM_{*j}} \times 100. \tag{4}$$

The region-specific MEI focuses on a particular region denoted by the asterisk symbol (*) and shows the characteristics of population exchange between that region and all other regions. This can be seen as extracting a specific row from a matrix composed of local MEIs defined in Equation 3. The region-specific MEI is regional because it yields index values for all the regions except for the focal region. It is local because it is based on flow-level observations between the focal region and all the other regions. Taking this region-specific perspective is advantageous from an exploratory standpoint. Not only does it allow for a less clutter-prone flow maps anchored on a focal region, but more importantly, it enables other types of visualization such as choropleth maps or proportional symbol maps in addition to flow maps (S.-I. Lee and Lee 2021, 2023).

2.2 | The Age-Specific MEI (ASMEI)

We can consider a generic extension of the original MEIs to include any categories that define the composition of people, leading to specific MEIs (SMEIs), without losing generality. However, this discussion focuses solely on age-specific MEIs (ASMEIs), though other types of SMEIs, such as gender-specific, race-specific, ethnicity-specific, and occupation-specific MEIs, are also possible. The ASMEI can be presented for the four different spatial scales as follows:

$$ASMEI_i^k = \frac{IM_i^k - OM_i^k}{IM_i^k + OM_i^k} \times 100 = \frac{NM_i^k}{GM_i^k} \times 100, \tag{5}$$

$$ASMEI^k = \frac{\sum_i \left|IM_i^k - OM_i^k\right|}{\sum_i \left(IM_i^k + OM_i^k\right)} \times 100 = \frac{\sum_i \left|NM_i^k\right|}{\sum_i GM_i^k} \times 100, \tag{6}$$

$$ASMEI_{ij}^k = \frac{Y_{ij}^k - Y_{ji}^k}{Y_{ij}^k + Y_{ji}^k} \times 100 = \frac{NM_{ij}^k}{GM_{ij}^k} \times 100, \tag{7}$$

$$ASMEI_{*j}^k = \frac{Y_{*j}^k - Y_{j*}^k}{Y_{*j}^k + Y_{j*}^k} \times 100 = \frac{NM_{*j}^k}{GM_{*j}^k} \times 100, \tag{8}$$

where k denotes a particular age group. The set of Equations (5)–(8) can be seen as a simple extension of that of Equations (1)–(4), respectively. ASMEIs measure the degree to which migration imbalance at each age group should contribute to population redistribution of that particular age group. They can be interpreted in the same way as the original MEIs, but for each age group.

Studies using the global ASMEI typically analyze temporal trends across age groups to assess how distinct each age group is regarding the directionality of population exchange over time at the country level. This helps identify whether certain age groups contribute more or less to the overall impact of migration on population redistribution compared to others (Ishikawa 2020; Stillwell et al. 2001). Studies based on the regional ASMEI usually compare spatial patterns of ASMEIs for several age groups (Stillwell et al. 2001). A similar approach has been applied for the ethnicity-specific MEIs (Stillwell and Hussain 2010). The most common level of age-specific effectiveness studies is the local level. Plane et al. (2005) developed an up-and-down effectiveness graph that clearly illustrates the direction and magnitude of migratory exchanges between regional categories. This method has been applied to internal migration data in various countries, including the United States (Plane et al. 2005; Plane and Jurjevich 2009), Canada (Newbold 2011), the Netherlands (de Jong et al. 2016), Russia (Mkrtchyan and Gilmanov 2023), and Japan (Kotsubo and Nakaya 2024).

Using ASMEIs, we can examine the uniqueness of each age group concerning the first aspect. However, age specificity is distinct from age collectivity. By 'age collectivity', I refer to the overall impact made by all ASMEIs combined. We hypothesize that by aggregating all ASMEIs, it would be possible to develop a new set of measures that capture disparities within ASMEIs or age-related disparities in MEIs. Moreover, this new set of measures could serve as an indirect indicator of the second aspect of migration effectiveness, which we will discuss in more details in the next section.

2.3 | Extending the MEI: The Age-Weighted MEI (AWMEI)

We now attempt to extend the original MEI based on the notion of age specificity. Equation (1) can be rewritten to incorporate age groups as follows:

$$\begin{aligned} MEI_i &= \frac{IM_i - OM_i}{IM_i + OM_i} \times 100 = \frac{NM_i}{GM_i} \times 100 \\ &= \frac{\left(IM_i^1 - OM_i^1\right) + \left(IM_i^2 - OM_i^2\right) + \ldots + \left(IM_i^k - OM_i^k\right) + \ldots + \left(IM_i^K - OM_i^K\right)}{\left(IM_i^1 + OM_i^1\right) + \left(IM_i^2 + OM_i^2\right) + \ldots + \left(IM_i^k + OM_i^k\right) + \ldots + \left(IM_i^K + OM_i^K\right)} \times 100 = \frac{\sum_k NM_i^k}{\sum_k GM_i^k} \times 100 \\ &= \frac{\sum_k NM_i^k}{GM_i} \times 100. \end{aligned} \tag{9}$$

The reason why this regional MEI cannot distinguish Regions A and B in Figure 1 is that the Region B's extreme age disparity, one-directional in-migration for young people and one-directional out-migration for elderly people just cancels out for opposite sign. One of the ways to avoid this cancelling-out and consider the whole range of age-specific unidirectionality is to take absolute values of the numerator in Equation (9) as follows.

$$AWMEI_i = \frac{\left|IM_i^1 - OM_i^1\right| + \left|IM_i^2 - OM_i^2\right| + \ldots + \left|IM_i^k - OM_i^k\right| + \ldots + \left|IM_i^K - OM_i^K\right|}{\left(IM_i^1 + OM_i^1\right) + \left(IM_i^2 + OM_i^2\right) + \ldots + \left(IM_i^k + OM_i^k\right) + \ldots + \left(IM_i^K + OM_i^K\right)} \times 100 = \frac{\sum_k \left|NM_i^k\right|}{GM_i} \times 100. \tag{10}$$

The term 'age-weighted MEI' (AWMEI) is proposed to denote this phenomenon at the regional scale, since it can essentially be conceptualized as a weighted sum of regional ASMEIs as follows.

$$\begin{aligned} AWMEI_i &= \frac{\sum_k \left|NM_i^k\right|}{GM_i} \times 100 = \sum_k \left(\frac{\left|NM_i^k\right|}{GM_i^k} \times \frac{GM_i^k}{GM_i}\right) \\ &\times 100 = \sum_k \left[\left(\frac{\left|NM_i^k\right|}{GM_i^k} \times 100\right) \times \frac{GM_i^k}{GM_i}\right] \\ &= \sum_k \left(\left|ASMEI_i^k\right| \times \frac{GM_i^k}{GM_i}\right). \end{aligned} \tag{11}$$

It is now clear that AWMEIs are weighted sums of the absolute values of ASMEIs. The weights represent the share of a particular age group in gross migration, which essentially reflects the size of that age group. Thus, AWMEIs can be defined as capturing the *collective* degree to which *any* age group contribute to population redistribution, while original MEIs capture the degree to which *all* age groups *collectively* contribute to population redistribution and ASMEIs capture the degree to which *each* age group contributes to population redistribution of that particular age group.

Let's take a closer look at the properties of AWMEIs. First of all, the measure is always positive and ranges from 0 to 100. It is 0 when the net migration is 0 across all age groups individually. It is 100 when migration flows are uniformly one-directional across all age groups, meaning that every age group experiences either exclusively out-migration or exclusively in-migration. Second, AWMEIs allow for interesting interpretations in comparison to original MEIs when the latter is transformed to absolute values. AWMEIs are always greater than or equal to absolute MEIs. The only condition of the equality of AWMEIs and absolute MEIs is that net migration signs are all the same across the age groups. The difference between the AWMEI and the absolute MEI reflects the extent to which positive and negative net migration values across age groups offset each other, thereby reducing the overall net migration captured by the MEI. In summary, two conditions must be met for the AWMEI to attain high value. First, the magnitude of net migration across age groups must be considerable. When all age groups exhibit migration in the same direction (i.e., share the same sign), the AWMEI equals the absolute MEI, and this magnitude alone determines the index. Second, substantial variation in the direction of net migration across age groups must be present, particularly among those exhibiting significant net migration values. The heterogeneity of these signs results in a reduction of the overall net migration captured by the MEI, thereby creating a discrepancy between the AWMEI and the absolute MEI.

To motivate the extension of the original MEIs to better account for the second aspect of migration effectiveness—its impact on population structure—we present a more realistic hypothetical example. This example considers three age groups (0–19, 20–44, and 45 and older) and compares two regions, A and B, representing typical urban and rural areas, respectively (Table 1).

According to the original MEIs (Equation 1), both regions are not differentiated, as each has a MEI of zero due to balanced total

TABLE 1 | Age-specific migration flows, net migration and effectiveness indices (MEI, ASMEI, AWMEI) for two hypothetical regions.

	Region A					Region B				
Age groups	In	Out	Gross	Net	ASMEI	In	Out	Gross	Net	ASMEI
0–19	7	6	13	1	7.7	7	8	15	−1	−6.7
20–44	30	25	55	5	9.1	22	23	45	−1	−2.2
45+	13	19	32	−6	−18.8	21	19	40	2	5.0
Sum	50	50	100	0		50	50	100	0	
Measures	$MEI_A = 0$ $AWMEI_A = 12$					$MEI_B = 0$ $AWMEI_B = 4$				

in- and out-migration. However, the ASMEIs (Equation 5) reveal substantial differences. Regions A and B exhibit ASMEIs with opposite signs across all age groups, and the absolute ASMEI values are consistently larger for Region A. This indicates that migration flows in Region A are not only more age-selective but also more impactful in terms of altering the regional population composition compared to Region B. In contrast, Region B has smaller and more balanced ASMEIs. This second aspect of migration effectiveness is effectively captured by the AWMEI (Equation 11). Calculated as the weighted average of the absolute ASMEIs, the AWMEI quantifies age-related disparities:

$$AWMEI_A = \frac{1+5+|-6|}{100}\times 100 = 7.7\times\frac{13}{100} + 9.1\times\frac{55}{100} + |-18.8|\times\frac{32}{100} = 12,$$

$$AWMEI_B = \frac{|-1|+|-1|+2}{100}\times 100 = |-6.7|\times\frac{15}{100} + |-2.2|\times\frac{45}{100} + 5.0\times\frac{40}{100} = 4.$$

Thus, migration is approximately three times more effective in altering the population structure of Region A than Region B, despite identical MEI values. This distinction highlights the added value of AWMEI in identifying nuanced demographic effects that the MEI and ASMEI alone cannot fully convey.

Subsequently, global and local versions of AWMEIs are formulated and expressed in terms of the corresponding ASMEIs as follows:

$$\begin{aligned} AWMEI &= \frac{\sum_i\sum_k \left|NM_i^k\right|}{\sum_i\sum_k GM_i^k}\times 100 = \frac{\sum_i\sum_k \left|NM_i^k\right|}{\sum_i GM_i}\times 100 \\ &= \sum\nolimits_k \left(\frac{\sum_i \left|NM_i^k\right|}{\sum_i GM_i^k}\times\frac{\sum_i GM_i^k}{\sum_i GM_i}\right)\times 100 \\ &= \sum\nolimits_k \left[\left(\frac{\sum_i \left|NM_i^k\right|}{\sum_i GM_i^k}\times 100\right)\times\frac{\sum_i GM_i^k}{\sum_i GM_i}\right] \\ &= \sum\nolimits_k \left(ASMEI^k\times\frac{\sum_i GM_i^k}{\sum_i GM_i}\right), \end{aligned} \tag{12}$$

$$\begin{aligned} AWMEI_{ij} &= \frac{\sum_k \left|Y_{ij}^k - Y_{ji}^k\right|}{\sum_k\left(Y_{ij}^k + Y_{ji}^k\right)}\times 100 = \frac{\sum_k \left|NM_{ij}^k\right|}{\sum_k GM_{ij}^k}\times 100 \\ &= \frac{\sum_k \left|NM_{ij}^k\right|}{GM_{ij}}\times 100 = \sum\nolimits_k\left(\frac{\left|NM_{ij}^k\right|}{GM_{ij}^k}\times\frac{GM_{ij}^k}{GM_{ij}}\right) \\ &\times 100 = \sum\nolimits_k\left[\left(\frac{\left|NM_{ij}^k\right|}{GM_{ij}^k}\times 100\right)\times\frac{GM_{ij}^k}{GM_{ij}}\right] \\ &= \sum\nolimits_k\left(\left|ASMEI_{ij}^k\right|\times\frac{GM_{ij}^k}{GM_{ij}}\right), \end{aligned} \tag{13}$$

$$\begin{aligned} AWMEI_{*j} &= \frac{\sum_k \left|Y_{*j}^k - Y_{j*}^k\right|}{\sum_k\left(Y_{*j}^k + Y_{j*}^k\right)}\times 100 = \frac{\sum_k \left|NM_{*j}^k\right|}{\sum_k GM_{*j}^k}\times 100 \\ &= \frac{\sum_k \left|NM_{*j}^k\right|}{GM_{*j}}\times 100 = \sum\nolimits_k\left(\frac{\left|NM_{*j}^k\right|}{GM_{*j}^k}\times\frac{GM_{*j}^k}{GM_{*j}}\right) \\ &\times 100 = \sum\nolimits_k\left[\left(\frac{\left|NM_{*j}^k\right|}{GM_{*j}^k}\times 100\right)\times\frac{GM_{*j}^k}{GM_{*j}}\right] \\ &= \sum\nolimits_k\left(\left|ASMEI_{*j}^k\right|\times\frac{GM_{*j}^k}{GM_{*j}}\right). \end{aligned} \tag{14}$$

We now have a complete set of AWMEIs, with properties consistent with the region-level AWMEIs. Their ranges are all from 0 to 100. A global AWMEI value of 100 indicates that all inter-regional migration flows are one-directional across all age groups. Similarly, a local AWMEI value of 100 signifies that migration exchanges between two regions are entirely one-directional for all age groups. We strongly believe that AWMEIs can be considered indirect measures of the second aspect of migration effectiveness. Although they do not directly compare the age composition of the population with that of migrants—specifically, net migrants—they offer a valuable starting point. This is because the second aspect of migration effectiveness is inherently linked to age disparities in net migration, which our new indices capture effectively.

3 | An Application to Internal Migration Data for South Korea

3.1 | Data and the Spatial Framework

We applied our measures to origin-destination migration data in South Korea from 2001 to 2022, using 17 5-year age groups ranging from 0–4 to over 80. There are two major data sources for migration in South Korea: resident registration data and census sample data (S.-I. Lee and Cho 2024; Y. Lee and Kim 2020). The former offers several advantages over the latter. First, it provides better data coverage, as it captures event data, unlike the census, which only records transitions (Bell et al. 2015, 2020; Charles-Edwards et al. 2019). Second, the resident registration data offers superior temporal resolution, providing consistent yearly or even monthly data, whereas the census data are collected every 5 years. All the data are available at KOSIS (KOrean Statistical Information Service) (https://kosis.kr/).

Our analysis utilizes a specific spatial framework consisting of 162 areal units (Figure 2). This framework lies between the first-tier level, which includes 17 metropolitan cities and provinces, and the second-tier level, which includes 229 areal units comprising metropolitan districts, regional cities and local counties, as defined in the standard Korean administrative geography (Y. Lee and Kim 2020). The spatial framework is constructed by merging the metropolitan cities from the first-tier, represented by the shaded areas in Figure 1, with regional cities and local counties from the second-tier. This approach has been believed to offer a

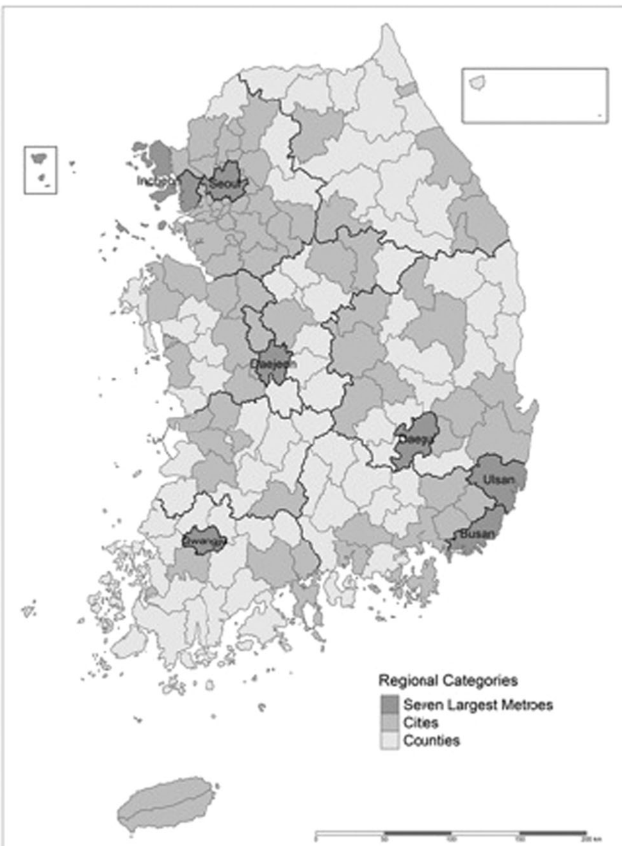

FIGURE 2 | A system of administrative areal units in South Korea as of 2022.

clearer representation of migration patterns than analyzing the first-tier or second-tier alone (S.-I. Lee and Kim 2021, 2022). To prevent data inconsistencies (Duke-Williams and Stillwell 2010) and potential issues related to the modifiable areal unit problem (MAUP) arising from changes in administrative boundaries (Chatagnier and Stillwell 2021; Stillwell et al. 2018), data for all-years were adjusted to align with the administrative districts as of 31 December 2022.

3.2 | Results

3.2.1 | A Global Scale Analysis

Figure 3 shows how the systemwide AWMEIs have changed over time in comparison to original MEIs. Overall, they show very similar trends. The MEI over the 22-year period ranges roughly between 6% and 9%, indicating that the proportion of net migration, which leads to population redistribution, is about 6%–9% of total migration. For a detailed interpretation of the temporal trend of MEIs, refer to S.-I. Lee and Lee (2023). The temporal trend of AWMEIs closely mirrors the fluctuations of the MEI, albeit with consistently higher values. The values range from approximately 8%–12%, indicating that the proportion of inter-regional migration contributing to population redistribution of any age group falls within this range.

As previously noted, the key issue is the difference between AWMEIs and MEIs. This difference represents the amount of net migration that would have been nullified in the original MEIs due to differences in the sign of net migration across age groups. Therefore, when AWMEIs and MEIs are similar, it indicates that the overall migration trend is consistent across all age groups, while a larger difference suggests that the overall trend and the trend for individual age groups differ. As shown by the line at the bottom of Figure 3, there is a clear trend of increasing divergence between AWMEIs and MEIs over time. The difference between the two indices remained around the mid-1 percentage point range until the mid-2000s, surpassed 2 percentage points in 2010, and continued to rise steadily, reaching the mid-2 percentage point range in the late 2010s, 3 percentage points in 2021, and the mid-3 percentage point range in 2022. This phenomenon can reasonably be inferred to result from increasing differences in migration patterns across age groups.

3.2.2 | A Regional Scale Analysis

Figure 4 illustrates the relationship between absolute MEIs and AWMEIs for 162 areal units in 2001 and 2022. Converting the original MEIs to absolute values facilitates a clearer comparison between these two measures. Several key observations can be made. First, as previously noted, AWMEIs are always equal to or greater than MEIs. Second, the linear relationship between the two measures is much stronger in 2001 compared to 2022, as reflected by Pearson's correlation coefficients of 0.951 in 2001 and 0.434 in 2022. This suggests that, over time, more regions have experienced mixed migration patterns, with gains in some age groups offset by losses in others. Third, the variability in AWMEIs differs according to the level of absolute MEIs. A closer look at the 2022 graph shows that MEIs within the range

FIGURE 3 | A comparison of MEIs and AWMEIs, 2001–2022.

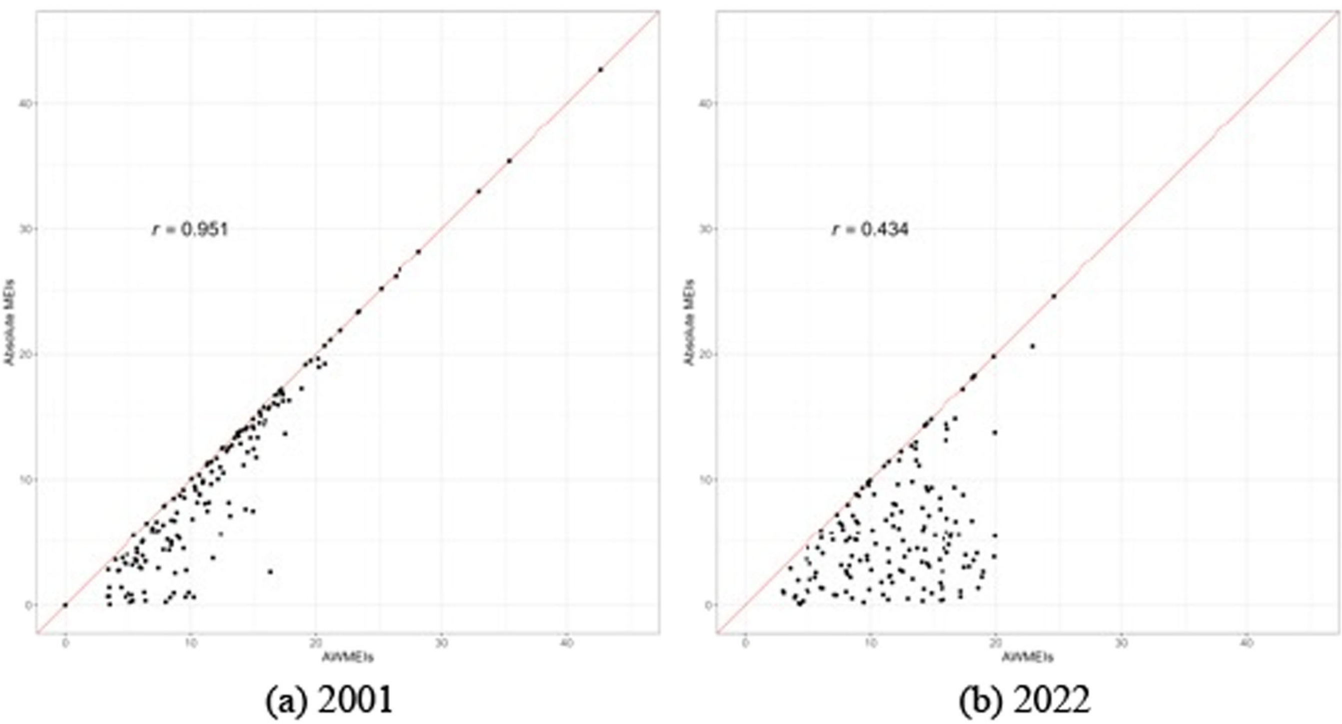

FIGURE 4 | A relationship between MEIs and AWMEIs in 2001 and 2022. (a) 2001; (b) 2022.

of 0–10 correspond to a wide range of AWMEIs. For instance, MEIs near 0 (indicating no migration effectiveness) are associated with AWMEIs ranging roughly from 3 to 20. The horizontal distance between any point on the graph and the red diagonal line represents the difference between the two measures for a given region, capturing the extent of net migration that is cancelled out in the original MEIs due to opposing directions across age groups.

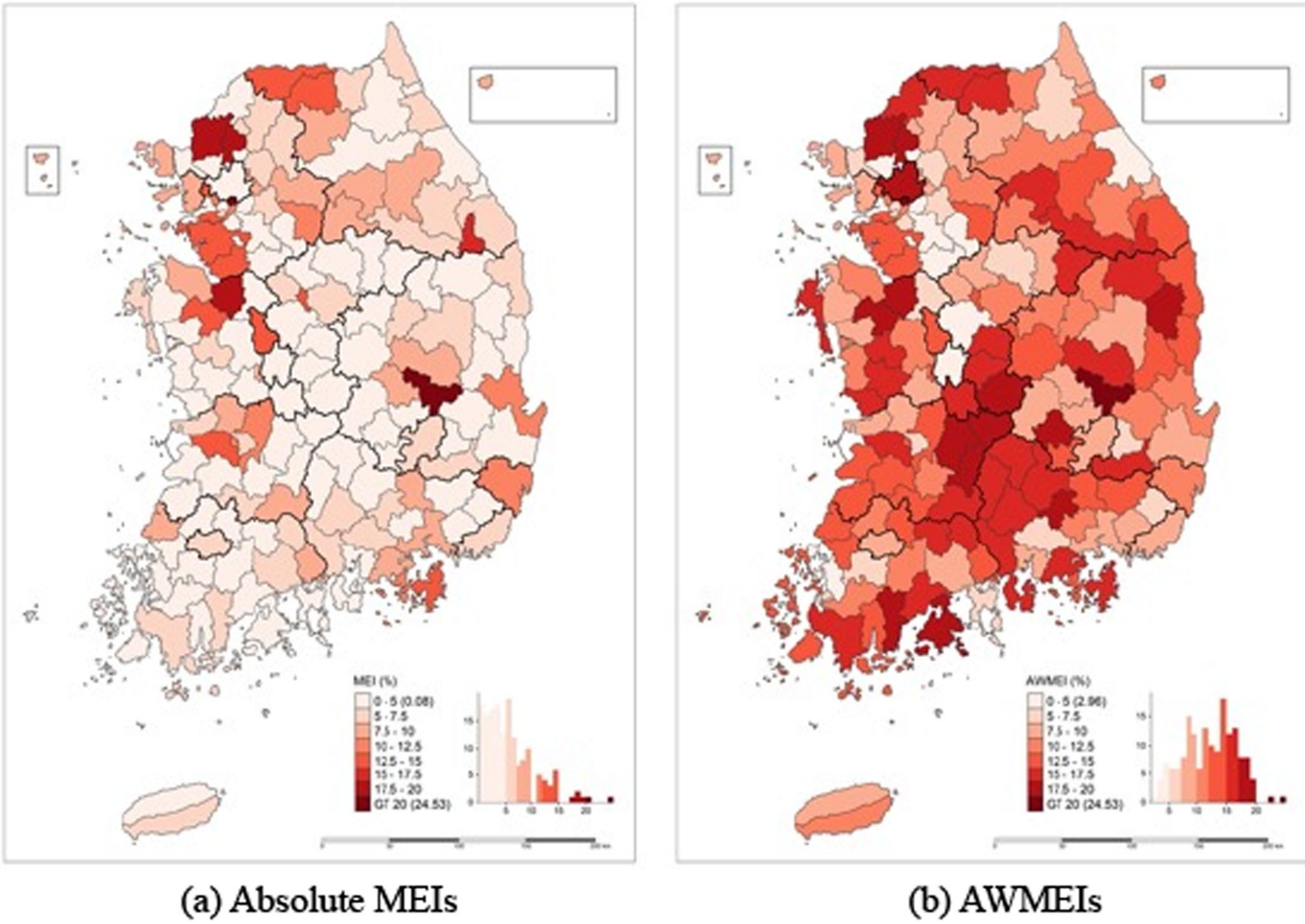

FIGURE 5 | A comparison of maps showing absolute MEIs and AWMEIs in 2022. (a) Absolute MEIs; (b) AWMEIs.

Figure 5 compares two maps depicting absolute MEIs and AWMEIs in 2022. As noted, AWMEIs are consistently greater than or equal to absolute MEIs. As implied by the moderate Pearson's correlation coefficient of 0.434 in Figure 4b, some regions are classified quite differently between the two maps. Among the largest metropolitan cities, Seoul, the capital city, stands out in comparison to regional metropolitan cities. Let's contrast it with Daejeon located in the middle of the country (see Figure 2). Both cities have low MEIs (−3.942 for Seoul and −1.948 for Daejeon), but their AWMEIs differ significantly (17.621 for Seoul vs. 4.136 for Daejeon). This difference reflects distinct migration patterns: Daejeon exhibits relatively balanced net migration across all age groups (relatively small net migration), while Seoul shows a sharp contrast, with substantial gains among those in their late teens and 20s and significant losses in all other age groups. The absolute MEI map actually hides Seoul's dominant role in shaping the age-specific migration landscape in South Korea—a dynamic that is more effectively revealed through ASMEI. Specifically, Seoul's ASMEI reaches 27.582 for the 20–24 age group, the highest in the country, and −21.027 for the 60–64 age group, the lowest. This reflects a sharp age selectivity in Seoul's migration exchange: nearly all regions (all but four) are losing young people (20–24) to Seoul, while most regions (all but eight) are gaining older adults (60–64) from Seoul (S.-I. Lee et al. 2024, 2025). These contrasting age-specific migration patterns underscore the demographic asymmetry embedded in inter-regional flows. Correspondingly, a key observation from Figure 5 is that rural counties tend to exhibit much larger AWMEIs relative to their absolute MEIs, reflecting the presence of substantial net migration flows in opposite directions across age groups—most notably, net out-migration among the young and net in-migration among the elderly.

For a more detailed analysis of these patterns, Figure 6 compares two regions with similarly low MEIs but markedly different AWMEIs. The figure adopts 'migration pyramids' (Kim 2010) to illustrate these contrasts, where out-migration is displayed on the left, in-migration on the right, and net migration overlaid—negative values on the left and positive values on the right. Both indices can be interpreted through the relative areas of the migration pyramid bars. The combined areas of in- and out-migration bars represent gross migration. Net migration is visualized by the area difference between the right (net in-migration) and left (net out-migration) sides. The MEI is calculated as the ratio of this net difference to the gross total. In contrast, the AWMEI uses the sum of the net in- and out-migration areas in the numerator, capturing the total magnitude of age-specific net migration regardless of direction.

Although both Icheon-*si* and Hapcheon-*gun* exhibit near-zero MEIs, their AWMEIs differ substantially. Icheon-*si*, a typical regional city, shows relatively uniform migration direction across age groups, leading to a low AWMEI. Hapcheon-*gun*, a

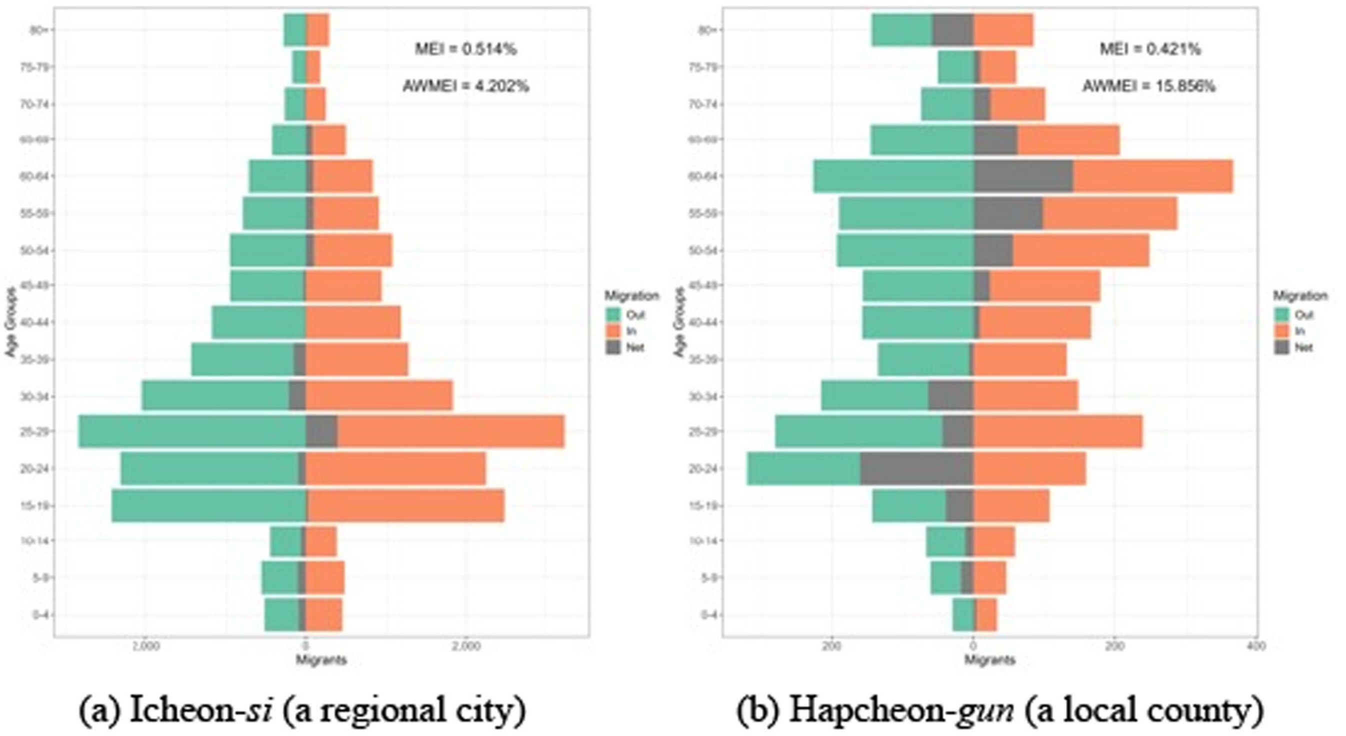

FIGURE 6 | A comparison of migration pyramids of two regions in 2022. (a) Icheon-*si* (a regional city); (b) Hapcheon-*gun* (a local county).

typical rural county, displays marked sign divergence by age, with net out-migration concentrated in the teens to 30s and net in-migration in the 40s to 60s, resulting in a high AWMEI.

3.2.3 | A Local Scale Analysis

Figure 7 presents the results from the local scale analyses. Figure 7a displays a map based on Equation (13), which measures the degree to which migration between two regions is unidirectional across all age groups, treating each age group's contribution separately. On this map, inter-regional lines are included only if they involve more than 1000 gross migrations and have AWMEIs > 25%. Out of a total of 26,082 pairs, only 69 pairs meet these criteria. Since AWMEI values for both regions in a pair must be positive and identical by definition, each region in the map serves as both an origin and a destination, unlike the local MEIs shown in Equation (3), where roles are distinct. The map clearly reveals a mono-polar concentration of migration towards Seoul, mirroring the pattern of strong centralization towards Tokyo observed in Japan (Ishikawa 2020). Seoul is involved in 26 out of the 69 pairs. This concentration is due not only to Seoul's size, which generates over 1000 gross migrations, but also to its highly heterogeneous exchanges with other regions across different age groups.

Figure 7b presents a Seoul-specific AWMEI map based on Equation (14). This map assigns AWMEI values to all regions based on their net migration exchanges with Seoul. Higher values reflect either large age-specific net migration magnitudes, consistent in direction, or substantial variation in migration direction across age groups, especially among those with large net flows. A clear pattern is that AWMEI values increase with distance from Seoul. A simplified description of South Korea's spatial structure is that regions closer to Seoul are generally more urbanized, with some exceptions for regional metropolitan areas and large cities. Seoul's population exchanges with nearby urban regions are relatively balanced and homogeneous across age groups, while exchanges with more distant, rural regions exhibit greater unidirectionality and heterogeneity.

To illustrate the two cases mentioned above, Figure 8 compares Bucheon-*si*, a large city in the capital region (Seoul and its surrounding areas), with Yesan-*gun*, a small rural county located farther from Seoul. As of 2022, Bucheon-*si*'s population (over 800,000) is more than 10 times that of Yesan-*gun*, and its gross migration with Seoul (26,998) is nearly 25 times larger. It is important to note that the migration pyramids in Figure 8 differ slightly from those in Figure 6: the x-axis represents net migration as a percentage of overall gross migration, rather than net migration itself. This adjustment allows for a more intuitive understanding of the measures: the sum of all x-axis values (%) represents the MEI, while the sum of the absolute x-axis values (%)—or the total of all the bar lengths—represents the AWMEI.

The net migration distribution across different age groups is notably similar between the two regions: Seoul attracts young people aged 15–29 but loses most other age groups—a common trend in Seoul's migratory relationships with various regions. The MEI value for Bucheon-*si* is higher than that of Yesan-*gun* due to its larger overall net migration. However, Bucheon-*si*'s AWMEI is much lower because of two factors: (1) the net migration relative to gross migration is much smaller, with < 1% across almost all age groups, indicating more balanced age-specific migration exchanges with Seoul; (2) the variation among age groups with substantial but oppositely signed net migration is also much smaller, showing only about a 2% differential compared to roughly 12% for Yesan-*gun*. These factors

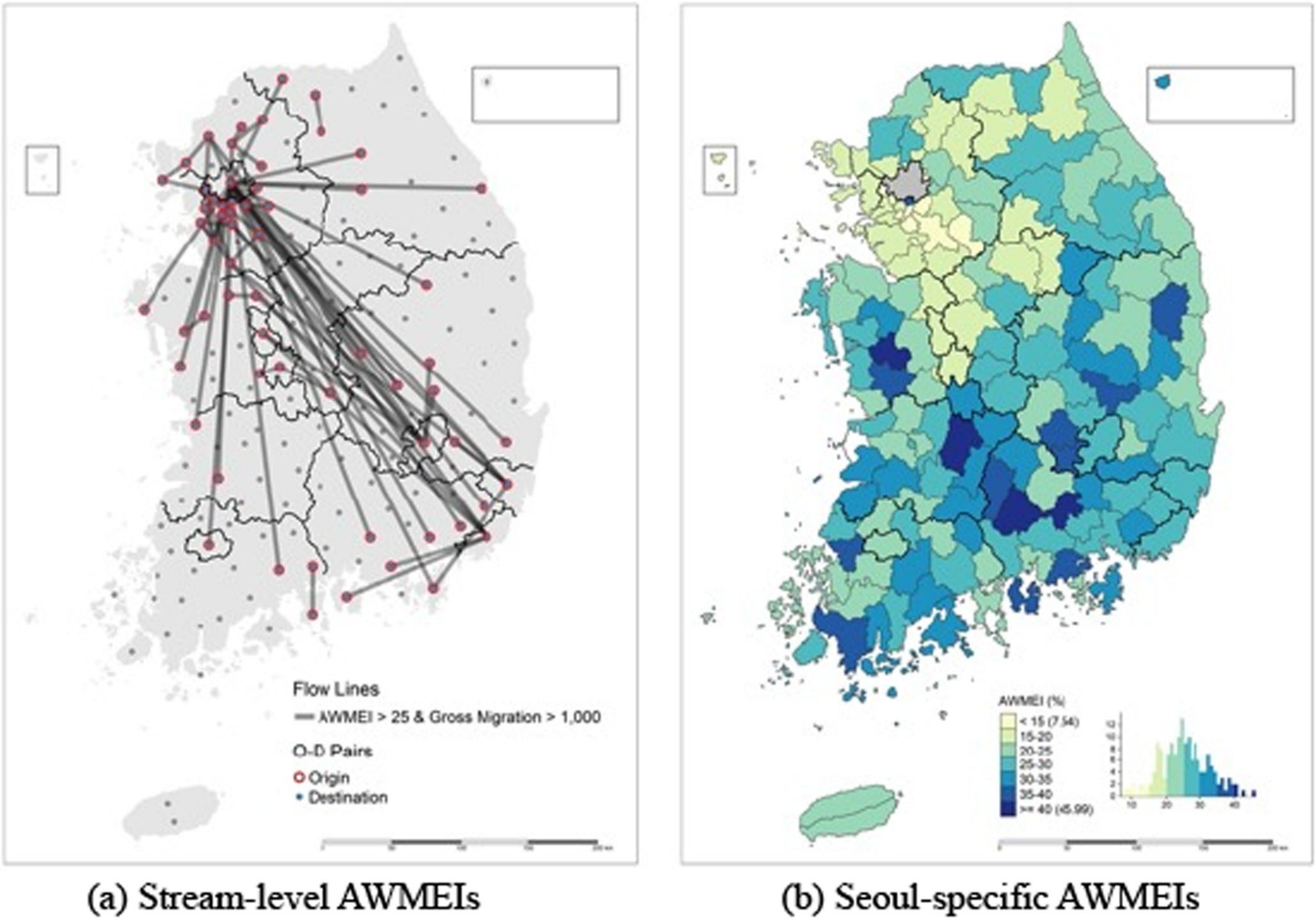

FIGURE 7 | AWMEIs at the local level in 2022. (a) Stream-level AWMEIs; (b) Seoul-specific AWMEIs.

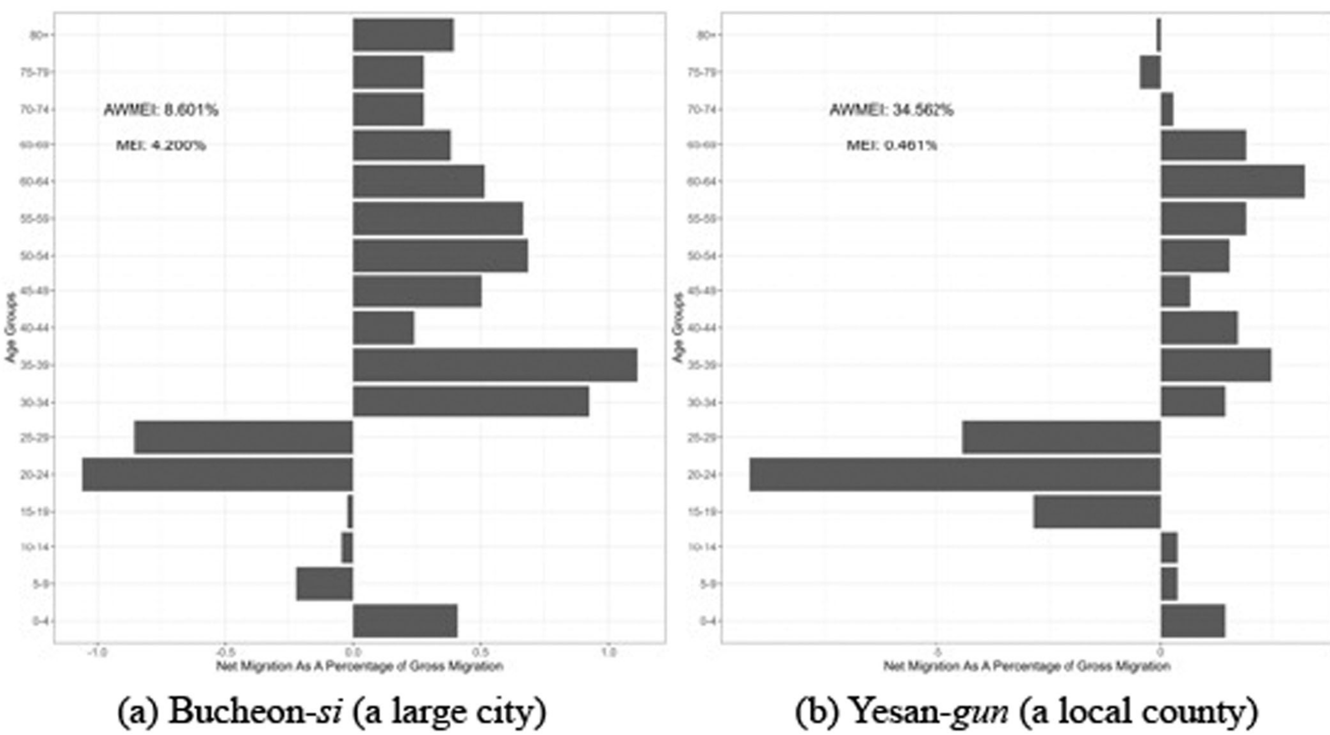

FIGURE 8 | Local migration exchanges between Seoul and two regions in 2022. (a) Bucheon-*si* (a large city); (b) Yesan-*gun* (a local county).

together result in Yesan-*gun* having a significantly higher AWMEI. This clearly illustrates that the AWMEI is determined by two factors: the magnitude of net migration relative to gross migration for each age group, and the variability of net migration signs among different age groups. In conclusion, Yesan-*gun* undergoes a more significant shift in population composition due to migration with Seoul compared to Bucheon-*si*, as reflected by the AWMEI, although its overall population size change is smaller than that of Bucheon-*si*, as indicated by the MEI.

4 | Conclusions

This study introduced the AWMEI as a novel and meaningful advancement in measuring migration effectiveness by explicitly incorporating age-specific variation into a single summary metric. While the traditional MEI offers insights into overall population redistribution, and the ASMEI enables disaggregated analysis by age, neither index captures the cumulative complexity of age-divergent migration patterns. The AWMEI fills this gap by assigning weights to net migration flows according to their age composition, thereby offering a more nuanced comprehension of migration's role in reshaping regional demographic structures.

Applying the AWMEI to South Korea's internal migration data from 2001 to 2022 reveals distinct advantages over the MEI. At the national scale, both indices display similar trends; however, the growing divergence between AWMEI and MEI over time indicates a widening age disparity in net migration. This trend suggests that an increasing number of regions experience simultaneous inflows and outflows across different age groups—such as net in-migration among older adults alongside net out-migration among younger cohorts.

At the regional scale, the AWMEI detects complex patterns obscured in aggregate MEI values. A comparison of absolute MEI and AWMEI values across 162 regions demonstrates that areas with near-zero MEIs may still exhibit substantial age-specific migration flows, which the AWMEI captures. This underscores the index's utility in revealing hidden demographic dynamics with critical implications for spatial planning and regional policy.

At the local scale, AWMEI further enhances interpretation by isolating directional differences in age-specific flows. For example, Seoul's contrasting migration exchanges with Bucheon-*si* and Yesan-*gun*—despite similar net migration balances—reveal fundamentally different age-selective patterns, made visible only through AWMEI. This local detail highlights the index's strength in identifying demographic shifts not apparent in aggregate indicators.

The observed widening gap and declining correlation between MEI and AWMEI (Figures 3 and 4) confirm that age disparities in migration have grown over time (Figure 5), and local-scale flows (Figures 7 and 8) reinforce this, showing increasingly divergent directions by age. These changes are driven primarily by two opposing trends: the concentration of young adult in-migrants (particularly aged 20–24) into Seoul and the dispersion of older adults (notably aged 60–64) from major cities into smaller towns and rural areas. Together, these dual processes are reshaping not only the spatial distribution of the population but also the age structure of regional populations—an effect far more evident when using AWMEI than MEI alone.

Although the AWMEI is not a direct measure of compositional change, its integration of age-specific information makes it highly relevant for demographic research. As internal migration becomes increasingly structured by age amid broader spatial demographic transitions, the AWMEI provides a robust, scalable framework for capturing the multidimensional impacts of migration. Furthermore, it should be noted that the aforementioned framework can be readily applied to any other subgroup of interest, such as ethnicity, gender, occupational categories, or educational attainment, thus enabling researchers to assess how migration patterns differ across these dimensions. This novel measure provides significant insights for future research and practical applications, particularly for researchers and policymakers seeking to understand and respond to regional demographic transformations invoked by migration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available in the KOrean Statistical Information Service at https://kosis.kr/. These data were derived from the following resources available in the public domain: Internal Migration Statistics, https://kosis.kr/publication/publicationThema.do.

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